Geology of the Istarú Quadrangle, Costa Rica

GEOLOGICAL SURVEY BULLETIN 1358

Prepared in cooperation with the Oficina de Defensa Civil and the Dirección de Geología, Minas, y Petróleo, Ministerio de Industria y Comercio, under the auspices of the Government of Costa Rica and the Agency for International Development, U.S. Department of State

Geology of the Istarú Quadrangle, Costa Rica

By RICHARD D. KRUSHENSKY

GEOLOGICAL SURVEY BULLETIN 1358

Prepared in cooperation with the Oficina de Defensa Civil and the Dirección de Geología, Minas, y Petróleo, Ministerio de Industria y Comercio, under the auspices of the Government of Costa Rica and the Agency for International Development, U.S. Department of State

A description of the volcanic deposits surrounding Irazú Volcano, and factors involved in slope stability and landslide control

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1972

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress catalog-card No. 72-600274

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $1.70 (paper cover)
Stock Number 2401–00263

CONTENTS

ILLUSTRATIONS

TABLE

GEOLOGY OF THE ISTARU QUADRANGLE, COSTA RICA

By RICHARD D. KRUSHENSKY

ABSTRACT

The Istarú quadrangle is underlain chiefly by volcanic rocks: lava flows, lahar deposits, conglomerate-breccia, air-fall tuff, and welded ash-flow tuff; there are small areas of marine and continental sedimentary rocks. The quadrangle is in the eastern part of the Cordillera Central, north of the Cordillera de Talamanca and southeast of the Cordillera del Guanacaste; it includes the major city of Cartago, 16 kilometers east of the national capital, San José. The Térraba Formation, San Miguel Limestone, and the Coris Formation are composed of marine siltstone and limestone and marine and continental sandstone of early Miocene age. The Térraba unconformably overlies the Pacacua Formation of probable Eocene–late Oligocene age outside the mapped area and is conformably overlain by the San Miguel Limestone. A basal breccia of San Miguel Limestone fragments in a matrix of sand of the Coris Formation indicates a slight disconformity between the San Miguel and the overlying Coris. These formations crop out in the southwest corner and along the southern border of the quadrangle.

Volcanic conglomerate-breccia, lava flows, bedded tuff, and welded ash-flow tuff of late Tertiary age, possibly Pliocene, compose the Aguacate and the Doán Formations in the southeast and southwest corners of the quadrangle. The Aguacate lies unconformably on the Pacacua Formation outside the quadrangle and is overlain disconformably by the Doán Formation. The top of the Doán Formation is eroded, and the formation is known to be overlain by other rock units in only one small area.

Ash-flow tuff and deltaic-lacustrine volcanic conglomerate of probable late Pleistocene age crop out in the south-central part of the mapped area and are of questionable stratigraphic position.

Lava flows, lahar deposits, bedded ash, and alluvium of Quaternary age cover about 90 percent of the area. Volcanic rocks of the Reventado, Sapper, Birrís, and Cervantes Formations compose the Irazú Group.

Structurally the area is simple. Lower Miocene rocks in the southwest part of the quadrangle have been folded into west-northwest-trending open anticlines and synclines, locally overthrust to the north and cut by right-lateral faults of minor displacement. The lower part of the Aguacate Formation in the southeast and southwest parts of the mapped area is also folded and cut by faults of minor displacement, but the upper part of the Aguacate in the southwest corner of the quadrangle, the Doán Formation, and all younger rocks appear to be undeformed in the mapped area. Rocks of the Irazú Group show initial dips that range from 5° to 36°; however, bedded lacustrine ash deposits in the Reventado Formation are horizontal and clearly are not affected by postdepositional deformation. A welded ash-flow

tuff in the canyon of the Rió Agua Caliente and all younger rocks in the quadrangle probably were deposited in the east-trending trough bordered on the south by the hypothetical Agua Caliente fault. The welded ash-flow tuff was deposited approximately 147,000±143,000 years before the present.

Mudflow deposits along streams draining the western and southern slopes of Irazú are only rudely bedded, and component clasts range from clay to boulders 4 meters on a side. The chief and economically most important deposits along the course of the Río Reventado and in the city of Cartago were derived chiefly from valley widening and from six active landslides in the Reventado watershed.

The future use and development of land on the flanks of Irazú should be conditioned by the fact that volcanic eruptions of ash and lava and the formation of potentially dangerous mudflows will recur. Eruptions will probably produce ash and lava flows sufficient to kill the vegetation in the area but insufficient to put the human and animal populations in imminent danger. Less likely are eruptions of ash-flow tuff like that which floors the Valle Central Occidental. Those deposits were produced by rapidly moving, fluid, and very hot ash and gas clouds like those that destroyed the city of St. Pierre, Martinique, in 1902.

INTRODUCTION

LOCATION AND ACCESSIBILITY OF THE AREA

Volcán Irazú, southernmost of the three active volcanoes of the Cordillera Central of Costa Rica, began a series of eruptions in March 1963 which continued intermittently until February 1965. Because of the results of these eruptions—the death of vegetation, the formation of destructive mudflows on the flanks of the volcano, and the extensive damage to coffee, tobacco, and citrus farms in the populous Valle Central Occidental—the Government of Costa Rica, through the Oficina de Defensa Civil, requested technical assistance from the U.S. Agency for International Development and the U.S. Geological Survey. This report is a product of the geologic investigation of control of mudflows, floods, and landslides and predictions of timing and type of future eruptions as undertaken by the U.S. Geological Survey in cooperation with the Oficina de Defensa Civil, and the Dirección de Geología, Minas, y Petróleo during the period November 1964 to March 1967.

The area of the Istarú quadrangle in central Costa Rica (pl. 1) includes the major part of the Volcán Irazú and part of the Valle Central Oriental. The quadrangle is bounded by lat 9°50′ and 10°00′ N., by long 83°45′ and 84°00′ W., and includes 565 square kilometers. Major east-west Highways Nos. 2, 10, and 230 cross the area and connect the major city of Cartago, in the southwest part of the area, with the national capital, San José, 16 km to the west. From these highways several all-weather gravel roads branch off to the northeast, north, and northwest. The area north of the Volcán Irazú–Cerro Pico Piedra divide near the northern border of the mapped area has no roads and only a few trails, and the southeast corner of the area has only one all-weather gravel road. Oxcart and foot trails, generally not passable by a four-wheel-drive vehicle, give access to most of the area south of the main east-west drainage divide. Most of the land in the area is used for dairy, vegetable, or coffee farming.

The mapped area (pl. 2) is dominated by the mass of Volcán Irazú, a locally deeply eroded cone whose summit is at an altitude of 3,432 meters. The area is rugged; relief exceeds 2,700 m—from 732 m in the valley of the Río Reventazón to the summit of Irazú. The contrast between the northern and southern slopes of the Volcán Irazú–Cerro Pico Piedra divide is striking. Many of the rivers on the northern slopes are deeply entrenched, and lava flows and ash beds commonly crop out as cliffs, whereas only two rivers on the south side of the drainage divide, the Río Reventado and Río Tiribí, are entrenched for any great length, most flowing on mainly uneroded tops of lava flows. The northwestern third of the mapped area lies in the watersheds of the Río Virilla and Río Tiribí and drains to the Pacific Ocean. The rest of the area is drained by four major rivers, from west to east, the Sucio, Chirripó, Toro Amarillo, and Reventazón, all of which drain to the Caribbean Sea. Headwaters of the Ríos Sucio, Toro Amarillo and Chirripó are restricted to the northern side of the Volcán Irazú–Cerro Pico Piedra divide; the Río Reventazón and its tributaries drain most of the mapped area.

PREVIOUS WORK

Previous geologic studies of parts of the Istarú quadrangle have been reconnaissance or restricted to small areas of economic interest. A reconnaissance pedologic-geologic study by Dondoli and Torres (1954) included the Cartago-Paraíso area and the valley of the Río Reventazón. Umaña (1964) studied the geology of the Cachí damsite just upstream from the junction of the Río Reventazón and Río Urasca; Woodring and Malavassi (1961) noted the fauna of beds here included in the Térraba, San Miguel, and Coris Formations; and Escalante (1965) reported on the geology of the Río Reventado valley and later (1966) studied the geology of the Tertiary section in the southeast corner of the present mapped area. As part of the U.S. Geological Survey study resulting from the recent eruptions of Volcán Irazú, Murata, Dondoli, and Saenz (1966) reviewed the recent eruptions and their effects, noted methods of eruption prediction, and suggested further work. Krushensky and Escalante (1967) reported on the eruptive activity of Volcán Irazú and Volcán Poás between November 1964 and July 1965.

Geologic studies in areas adjacent to the Istarú quadrangle include those by Romanes (1912) near Tres Ríos, by Crosby (1942) in the canyon of the Río Virilla west of San José, and by Williams (1952) in the Valle Central Occidental.

PURPOSE AND METHOD OF INVESTIGATION

The purpose of the investigation was twofold: to develop a general understanding of the history of volcanism in the Irazú area and to study geologic conditions and other factors involved in slope stability and slope-control programs as related to land use. An understanding of past volcanic activity and any trends detected might be useful in planning long-term land use and development. Detailed studies of smaller areas, especially the watersheds of the Río Reventado and Río Tiribí, could be of immediate use in flood, mudflow, and landslide-control programs. As mapping of the quadrangle progressed, it became clear that significant information concerning the relationship of the late Tertiary Talamancan orogeny and the beginning of Quaternary volcanism could be gained in the Irazú area. This report describes the general geology of the Istarú quadrangle and the petrology of rocks in the area, and it draws certain conclusions regarding land use and development.

Fieldwork started in December 1964; 1:20,000-scale aerial photographs taken in 1956 and 1:12,000-scale aerial photographs of the mudflow-devastated areas taken in 1964 were used. Fieldwork from December 1964 through February 1965 was concerned with the study of the eruptive phase of Volcán Irazú; detailed study and mapping of parts of the watersheds of the Río Tiribí, Río Virilla, and Río Reventado and geologic mapping of the Istarú quadrangle took about 18 months, March 1965 to September 1966. Geology was transferred from aerial photographs to the topographic base map by inspection. The topographic base, compiled by photogrammetric methods, was published by the Instituto Geográfico de Costa Rica at a scale of 1:50,000. Petrographic studies included the examination of about 200 thin sections and the comparison of new analyses of volcanic rocks from the Istarú quadrangle and those from other volcanoes in the Cordillera Central and the Cordillera del Guanacaste.

ACKNOWLEDGMENTS

Costa Ricans who have assisted the writer in completing this study are too numerous to list individually, but I wish to thank some of those who contributed significantly: Mr. Gregorio Escalante, for the many interesting and challenging days spent in the field and in discussion and for his considerable contribution to the geology of the southeast corner of the mapped area; Dr. César Dondoli, Director, Department of Geology, Mines, and Petroleum, Ministry of Industries and Commerce, for his continued interest and review of this manuscript; Ing. Rodolfo Dobles, formerly Director, Office of Civil Defense, and Ing. Fernando Lizano, Director, Office of Civil Defense, for cooperation extended during the study; and Mr. Rodolfo Lachner, for hospitality and assistance freely given during the course of the fieldwork.

Mr. A. E. Farwell, Director, U.S. Agency for International Development Mission to Costa Rica, lent considerable support to the study. Frank D. Spencer, engineering geologist, U.S. Geological Survey, reviewed the manuscript, made greatly appreciated suggestions, and also accompanied the writer in the field on many occasions.

GEOLOGIC SETTING OF THE ISTARU QUADRANGLE

The Cordillera Central of Costa Rica lies within the northwest-trending inner arc of the southern Central American orogen (Dengo, 1962a, p. 134); it is enclosed on the southwest by an outer arc of folded and faulted sedimentary, volcanic, and igneous rocks and on the northeast by the sedimentary rocks of Limon basin. Vaughan (1918) previously had identified these three structural units as part of a tectonic province which included Nicaragua, Costa Rica, and Panama. Later workers in the area have followed Vaughan's usage (Woodring, 1928; Schuchert, 1935; Sapper, 1937; Eardley 1951; Weyl, 1961; and Dengo, 1962a).

The Cordillera Central is along the northern border of an east-west tectonic trend that cuts across the dominant northwest-southeast structural trend of the country. To the south, in the Cerros de la Carpintera, the predominantly volcanic rocks of the Cordillera Central overlie a belt of folded and faulted sedimentary and volcanic rocks of early Miocene to Pliocene(?) age; to the east they lie on the Suretka Formation and on older deformed Tertiary formations. To the west, rocks of the Cordillera Central lie on locally folded rocks of the Aguacate Formation, of late Tertiary age. The southern part of the inner arc extends into Panama and consists of northwest-trending folded sedimentary, volcanic, and intrusive rocks that range in age from Eocene to early Miocene. The northern part of the inner arc consists of a northward extension of the folded Aguacate Formation and, in the northwestern part of Costa Rica, of the Guanacaste volcanic rocks of Quaternary age.

Sedimentary and volcanic rocks—chiefly sandstone, shale, limestone, volcanic conglomerate, and ash-flow tuff of late Tertiary age and andesitic lava flows and ash beds, mudflows, and alluvium of Pleistocene and Holocene age—are exposed in the Istarú quadrangle (pl. 2). Approximately 90 percent of the mapped area is covered by volcanic rocks of Quaternary age; rocks of Tertiary age crop out chiefly in the southeastern and southwestern parts of the area. Rock units not previously mapped or formally named have been named where appropriate and have been described as fully as possible in accordance with suggestions published by the American Commission on Stratigraphic Nomenclature (1961).

Two sequences of rocks of Tertiary age crop out in the mapped area. The older sequence, of Miocene age, consists of fine-grained sandstone, siltstone, shale, and some limestone of the Térraba Formation, the San Miguel Limestone, and the Coris Formation. These formations crop out in two small isolated hills on the southern border and in the southwestern part of the mapped area. The younger sequence of Tertiary rocks, possibly ranging in age from late Miocene to Pliocene, consists of volcanic conglomerate, breccia, sandstone, andesitic lava flows, and ash-flow tuff of the Aguacate and Doán Formations. These formations crop out in the southwestern and southeastern parts of the mapped area.

Quaternary rocks include two ash-flow tuffs, the Ujarráz Formation, and the Irazú Group.

STRATIGRAPHY

TERTIARY SYSTEM

MIOCENE SERIES

TERRABA FORMATION

Siltstone and shale of the Térraba Formation crop out south of the Cerros de la Carpintera in the southwest corner of the mapped area and in a small isolated hill just south of Tejar on the southern border of the quadrangle. The formation was named by Dengo (1961, p. 48) for a 1,300-m section of shale and siltstone that crops out along the Río Térraba between El Cajón and the mouth of the Río Changuina.

Unweathered outcrops of the Térraba Formation are rare, and weathered outcrops are easily confused with the Coris Formation. The only unweathered outcrop of the Térraba seen in the mapped area is in the roadcut in the low ridge just south of the hot springs (termales) in the southwest corner of the mapped area. There the

Térraba is a dark-greenish-gray siltstone that weathers to light olive gray and light gray or white. Bedding is relatively even and ranges from laminae 3 millimeters thick to thin beds 3 centimeters thick. Both unweathered and weathered outcrops are cut by joints spaced 1 to 2 cm apart. Weathered outcrops of the Térraba near Bermejo and southwest of Coris range from light gray to light reddish or orange brown and are very fine grained sandstone with a minor argillaceous matrix. Generally, the more argillaceous the rock, the darker the color of the residual soil and weathered rock.

A thin massive dense grayish-yellow limestone interbedded with siltstone of the Térraba crops out on the southwest border of the mapped area northwest of Bermejo. Unlike the San Miguel Limestone, this limetsone contains no pectens. R. Castillo M. (Dirección General de Geología, Minas, y Petróleo; Ministerio de Industria y Comercio, oral commun., 1966) reported this same limestone near Asserí, 10 km to the west.

The Térraba Formation is overlain by the San Miguel Limestone of early Miocene age (W. P. Woodring, oral commun., 1965; Cooke, Gardner, and Woodring, 1943, chart; and E. Malavassi V., Dirección General de Geología, Minas, y Petróleo, Ministerio de Industria y Comercio, oral commun., 1966). The upper contact, although poorly exposed in the northern face of the ridge just south of Quebrada Barahona and in the southern face of the ridge west and south of Coris, appears to be comformable. The base of the Térraba is not exposed in the quadrangle, but in the Tapantí quadrangle to the south, the Térraba Formation unconformably overlies purple volcanic conglomerate and sandstone of the Pacacua Formation, of probable Eocene–early Oligocene age. Microfossils collected by E. Malavassi V. and the writer from outcrops of the Térraba Formation in the area of Bermejo have been described by M. Ruth Todd (U.S. Geol. Survey, written commun., 1967) as comprising "a rich but rather poorly preserved assemblage of predominantly planktonic Foraminifera." Among many species, the following were recognized:

Globigerinoides trilobus (Reuss)
Globoquadrina dehiscens (Chapman, Parr, and Collins)
Globorotalia opima Bolli
Nonion mediocostatum (Cushman)
Plectofrondicularia sp. aff. *P. alazanensis* Cushman
Uvigerina sp.
Bulimina sp.
Bolivina sp.

Todd suggested that the best estimate for the age of the sample would be early or middle Miocene. However, Dengo (1961, p. 49), following Lohmann (1934, p. 14), assigned the Térraba Formation an early or middle Oligocene age, chiefly on the basis of the presence of *Pecten exygonum optimum* and *Pyrula micronematica.*

SAN MIGUEL LIMESTONE

Outcrops of the San Miguel Limestone are near the crest of the ridge between Bermejo and Quebradillas, in a small ridge 0.4 km west of Coris, and in small isolated hills south of Tejar and just west of Hervidero. The San Miguel Limestone was named by Romanes (1912, p. 106) for a section (5–15 m thick) of fossiliferous pale-bluish-gray limestone that crops out from Patarrá, 15 km southeast of San José, to Agua Caliente. The type section is not specified, but it is presumed to have been at San Miguel where outcrops of the limestone are prominent.

The San Miguel Limestone is composed chiefly of very thick to thick-bedded fine- to medium-crystalline light-bluish-gray limestone. Local ill-defined zones or lenses consist of masses of broken fossil fragments cemented by finely crystalline calcite. Outcrops in the ridge south of Bermejo show widely spaced (1–3 m), very thin (1 cm) partings of argillaceous limestone or calcareous shale. Bedding surfaces are poorly defined, commonly undulating, and locally appear to be ripple marked. The weathered rock is pale grayish yellow and locally marked by fossil fragments that weather into positive relief. All outcrops except that near Hervidero show pods of fossils; pectens are abundant. *Lyropecten?* (*Nodipecten?*) sp. cf. *L. nodosus* has been identified from outcrops of the San Miguel at Patarrá 3 km northeast of the San Miguel type section and 4 km west of the Cerros de la Carpintera. Fossils collected and identified by E. Malavassi V. (Dirección General de Geología, Minas, y Petróleo, written commun., 1966) from the San Miguel Limestone in the Tapantí quadrangle, just southeast of Hervidero are:

Siphogenerina transversa Cushman
Uvigerina carapitana Hedberg
Uvigerina sp.
Nonion pompilioides (Fichtel and Moll)
Globobulimina pacifica Cushman
Orbulina universa d'Orbigny
Globigerina venezuelana Hedberg
Globigerinoides trilobus (Reuss)
Cibicides sp.

The San Miguel Limestone is overlain by the Coris Formation of early Miocene age, and in the outcrop near Hervidero the contact seems to be conformable, as both formations have the same attitude. However, the lower few meters of sandstone of the Coris Formation contain angular blocks of the San Miguel Limestone, which suggests a disconformable contact. The contact with the Térraba Formation is poorly exposed, but it appears conformable.

Woodring (1966, p. 43) noted that *Siphogenerina transversa* may be as old as late Oligocene but no younger than early Miocene, at which time it was best developed. Woodring had previously stated that a large assemblage including pelecypods collected from the Térraba–San Miguel–Coris equivalents near Turrúcares was "of Miocene age and they [the fossils] suggested middle Miocene" (Woodring and Malavassi, 1961, p. 496). The San Miguel Limestone present in the Istarú quadrangle is the same as that noted by Dondoli and Torres (1954, p. 16) as part of the "calcareous sandstone unit."

CORIS FORMATION

The Coris Formation, named by R. Castillo M. (Dirección General de Geología, Minas, y Petróleo, written commun., 1966) for a 380-m-thick section of sandstone and mudstone in the Alto Coris area 2.4 km northwest of the village of Coris, is generally poorly exposed in the mapped area. The Coris Formation crops out in the northwest-trending ridge just northeast of Coris, above the San Miguel Limestone in the ridge between Bermejo and Quebradillas, in the small hills south of Tejar and just west of Hervidero, and in the ridge south of Tobosi.

The major part of the Coris Formation exposed in the mapped area consists of light-yellowish-gray to dark-reddish-orange fine- to medium-grained argillaceous sandstone. Locally the rock is a well-sorted medium-grained white to pale-yellowish-gray or purple quartzose sandstone. Facies change in short distances both along and across strike. Locally, clay particles, originally lithic fragments of volcanic rocks, constitute as much as 40 percent of the sandstone. Highly argillaceous facies of the sandstone are commonly more deeply weathered and form valleys and gently rounded slopes; the rock is laminated to very thin bedded, and joints are closely spaced. The section of argillaceous sandstone 0.6 km northwest of Coris includes some thin (2–15 cm) and areally restricted silty and clayey lignite lenses. R. Castillo M. (oral commun., 1966) reported similar lignite lenses from the Coris at Higuito, 6 km southwest of the village of Coris. The quartzose sandstone facies crops out as resistant ridges that show thick to very thick bedding, widely spaced joints, and local crossbedding. Both the argillaceous and the quartzose facies are commonly friable. Locally, the quartose facies is a densely cemented orthoquartzite. The formation is approximately 60 m thick in the Istarú quadrangle.

The Coris and the normally overlying Aguacate Formation appear in fault contact south of Tejar and Hervidero just south of the mapped area. However, 12 km west of Tobosi along the road between Asserí and Tarbaca in the Abra and Caraigres quadrangles, quartzose and argillaceous sandstone of the Coris Formation is interbedded with and overlain by pale-green to white fine-grained air-fall tuff of the Aguacate Formation. The bottom contact with the San Miguel Limestone, already described, is disconformable in the mapped area. E. Malavassi V. (oral commun., 1966) has noted an angular unconformity between the Coris Formation and the San Miguel Limestone in the area of the Caraigres quadrangle to the southwest.

MIOCENE(?) AND (OR) PLIOCENE(?) SERIES

The younger sequence of Tertiary rocks crops out in the southeast and southwest corners of the mapped area and comprises the Aguacate and Doán Formations. These rocks are predominantly volcanic conglomerate, breccia, lava, and welded ash-flow tuff and bedded air-fall tuff.

AGUACATE FORMATION

The Aguacate Formation, formerly named by Dengo (1962a, p. 147; 1962b, p. 57) for an 800-m-thick section of basalt and andesite lava flows, volcanic breccia, and tuff in the Aguacate Mountains, crops out along the course of the Río Reventazón from Congo near the eastern border of the mapped area, to Joyas, up the Río Urasca, and south beyond Bajos Urasca. In the southwest corner of the mapped area the Aguacate crops out from Barrancas to the Río Purires.

The Aguacate Formation in the southeast corner of the mapped area is composed of volcanic conglomerate, breccia, lava flows, and a very small amount of tuff. The volcanic conglomerate and breccia constitute 75 to 80 percent of exposed rocks in this formation. These rocks have the appearance of lahar; that is, mudflow deposits composed of volcanic material. The deposits consist of a chaotic mixture of rock fragments ranging from pebbles to boulders, subangular to rounded, enclosed in a matrix of sand- and clay-sized materials, and they show neither bedding nor sorting. Boulders as much as 1 m on a side are common. The larger fresher rock fragments are from porphyritic augite-andesite and andesite lavas. Outlines of microphenocrysts of feldspar in the smaller sand-sized particles are generally preserved; the rocks from which these were derived also were clearly porphyritic lava, but the feldspars are too deeply weathered to make closer identification possible. Fresh clasts are medium to dark gray, generally very finely crystalline porphyritic andesite; many show phenocrysts of augite. The matrix pebbles and sand-sized lithic clasts are simply smaller grained, more weathered versions of coarser fragments. The matrix is commonly weathered to light-greenish-gray or yellowish-gray clay and feldspar and augite crystal fragments. Escalante (1966, p. 64) described the matrix as tuffaceous, but the rounding of particles and lack of volcanoclastic texture suggest an origin due to erosion rather than to primary volcanic activity.

Lava flows in the Aguacate Formation are rarely more than 5 m thick, and all are closely jointed (5–20 cm) and appear fresh in comparison with the lahars. All the Aguacate flows examined are porphyritic augite-andesite and andesite and are generally dark to medium gray and very finely crystalline. Locally, between Santiago and San Jerónimo, the Aguacate Formation consists of stratified volcanic conglomerate and sandstone. Lithologically the conglomerate looks much like the lahar deposits, but bedding is evident in both the sandstone and conglomerate, and coarser lithic clasts are rounded and subrounded. Tuffaceous parts of the Aguacate Formation in the southeast corner of the mapped area are difficult to separate with certainty, as the rocks are deeply weathered and outcrops are very poor. Thick soil and dense vegetation make thorough examination of all areas very difficult. The Aguacate Formation cropping out from the village of Urasca to the area directly west of Bajos Urasca was mapped originally by Escalante (1966, p. 65) as the tuffaceous lower part of the Doán Formation, but Escalante (oral commun., 1967) now agrees that the unit is best removed from the Doán and placed with the Aguacate Formation. Outcrops in roadcuts or quarries in the lava beds, notedly along the road between San Jerónimo and Puente Fajardo, show an irregular contact that suggests pre-Doán folding of the tuffs. Outcrops of tuff commonly show no bedding, and all outcrops are dark-orange-brown or hematite-red clay.

Outcrops of the Aguacate Formation between Barrancas and the Río Purires in the southwestern part of the quadrangle consist of interbedded fine-grained argillaceous sandstone and very fine grained thin-bedded tuff similar to that seen 12 km to the west along the Asserí-Tarbaca road. Both the sandstone and tuff are deeply weathered to a reddish-brown or orange-brown clay. Four km south of the quadrangle boundary, the sandstone-tuff sequence is overlain with apparent unconformity by a thick massive pale-gray or purplish-gray welded ash-flow tuff, which is also part of the Aguacate Formation.

Irregularly bedded and poorly sorted pale-blue-green clayey tuff similar to that near the base of the Aguacate Formation in the Caraigres quadrangle crops out in the canyon of the Río Cajón near the northern border of the Istarú quadrangle. The tuff changes little within the restricted area of outcrop. Individual beds are 5 to 8 cm thick, and rounded to subrounded dark-purplish-red pebbles of porphyritic andesite are common near the base of the exposed section. Broken crystals of highly altered plagioclase are common, constituting perhaps 25 percent of the rock. The matrix is very fine grained and is altered to pale-blue-green clay.

No fossils have been found in the Aguacate Formation in the Istarú quadrangle, but similar-appearing rocks in the Abra quadrangle to the east and in the Caraigres quadrangle unconformably overlie the lower Miocene facies equivalent of the San Miguel Limestone, the Turrúcares Formation, and are locally conformable with the Coris Formation. The Aguacate Formation is, therefore, no older than early Miocene and in part it may be as young as Pliocene (Dengo, 1962b, p. 57).

The upper contact of the Aguacate Formation is best seen in the faces of cliffs in the Cerro Cruces area where outcrops of the flat-lying Doán Formation unconformably overlie the folded Aguacate Formation. The lower contact is not seen in the mapped area, but 1.5 km south of the southern border of the Istarú quadrangle, near Cachí, the Aguacate Formation unconformably overlies the purple volcanic conglomerate-breccia-sandstone of the Pacacua Formation. In the Asserí-Tarbaca area along the mutual border of the Abra and Caraigres quadrangles, the Coris Formation grades into the overlying Aguacate Formation.

DOAN FORMATION

The Doán Formation originally named by Escalante (1966, p. 64) from the type locality at Cerro Doán 1.8 km south of the mapped area is here redefined. The Doán Formation as used in this paper consists of volcanic boulder conglomerate and some volcanic pebble conglomerate and volcanic conglomeratic sandstone. The Doán unconformably overlies the Aguacate Formation and is unconformably overlain by a welded ash-flow tuff at San Jerónimo. The Doán Formation forms spectacular white-weathering cliffs as much as 200 m high, such as those at Cerro Cruces. Within the Istarú quadrangle, the Doán Formation has a thickness of about 400 m; Escalante (1966, p. 65) noted that it may be more than 800 m thick to the south.

The tuff previously regarded as the base of the Doán Formation is identical with the tuff seen at the base of the Aguacate Formation in the Río Purires area in the southwest corner of the Istarú quadrangle and is included within the Aguacate Formation. The welded ash-flow tuff at San Jerónimo previously considered as the top of the Doán Formation has been separated from the formation because the tuff lies unconformably on the subhorizontal sequence of clastic rocks here defined as Doán and differs greatly from the Doán in both origin and lithology. The welded ash-flow tuff is now tentatively correlated with the ash-flow tuff that crops out in the canyon of the Río Agua Caliente beneath the Paraíso Member of the Reventado Formation.

The Doán Formation is composed of gray to very dark gray, very thick to thick-bedded, water-laid volcanic boulder conglomerate with some volcanic pebble conglomerate and volcanic conglomeratic sandstone. The boulder conglomerate, areally dominant, consists of angular to subrounded boulders and pebbles of dense dark-gray to black porphyritic andesite-basalt and porphyritic augite-andesite in a porous sandy matrix composed of lithic clasts like the larger fragments and commonly speckled with augite crystals and ocher. Phenocrysts of plagioclase and augite in the lithic clasts are large (0.5–1 cm) and abundant. Typically, the augite phenocrysts are weathered into positive relief. About 20 percent of the larger lithic clasts contain augite. Sandstone in the Doán Formation is like the matrix described above.

Corals found in the Doán Formation south of the mapped area have not been identified, and at present the upper limits of the formation are unknown. The Doán Formation does resemble the Suretka Formation of Pliocene(?) age (Dengo, 1962a, p. 149) and is here tentatively correlated with that formation. Dengo considered the Suretka a molasse facies produced by the rising mass of the Talamanca Range only a few kilometers to the south. The Doán, however, becomes finer in the direction of the Talamanca Range, is clearly marine in origin, at least to the south, and is not derived chiefly from a Talamanca source.

QUATERNARY SYSTEM

PLEISTOCENE SERIES

Volcanic deposits of Quaternary age, chiefly lava, lahar, ash, and some deposits of epiclastic rocks of volcanic origin, crop out over 90 percent of the Istarú quadrangle. Three areally restricted units, the Ujarráz Formation, the ash-flow tuff of San Jerónimo, and the ash-flow tuff of the Río Agua Caliente are of uncertain stratigraphic position. Rocks of the Irazú Group, areally are most extensive in the quadrangle, consist of lava, lahar, and ash and make up the Cervantes, Birrís, Sapper, and Reventado Formations. Alluvial deposits of Holocene age are mainly along the streams and are locally extensive in the western part of the mapped area.

ASH-FLOW TUFF OF THE RIO AGUA CALIENTE

A welded ash-flow tuff, undescribed by other workers, crops out in the canyon of the Río Agua Caliente east of Hervidero near the central southern margin of the quadrangle. The upper contact is conformable with the overlying Reventado Formation, and the unit unconformably overlies the folded Térraba Formation. Formal naming of this unit, clearly separable from the Reventado Formation on lithologic grounds, is delayed until detailed study can be made in areas of more extensive outcrop.

The ash-flow tuff as exposed consists of a grayish- to yellowish-green poorly welded section about 3 m thick over a progressively more densely welded section as much as 25 m thick. The poorly welded upper part is well preserved and free of channeling; it contains abundant dark-yellowish-orange pumice fragments that weather into negative relief and show no stretching and only slight flattening. Phenocrysts of plagioclase are rare in this upper section, and lithic clasts are scarce. Pumice clasts have collapsed completely, and small scattered fiamme (flame-shaped glassy inclusions) are dominant as little as 5 m below the top of the unit. This moderately welded part of the tuff still shows the grayish-yellow-green matrix, but small black vitric fiamme constitute about 20 percent of the rock. Progressive flattening of the pumice, increase in size and number of the fiamme, and compaction of the matrix result in densely welded tuff at no more than 8 m below the top of the ash-flow tuff unit. The most densely welded part of the tuff is medium to dark gray in overall appearance and shows uncommon grayish-yellow-green to light-gray lithic clasts that reach a size of 1.5 cm. The medium-gray matrix is abundant and consists of an intimate mixture of filaments of dense black glass, granular-appearing gray glass, and broken plagioclase phenocrysts. Black vitric fiamme as much as 6 cm long and 4 cm thick are abundant, making up perhaps 45 percent of the rock. These lenticles of black glass feather out into the matrix, and some show conspicuous streaks of colorless glass. Plagioclase phenocrysts are scarce in the fiamme, and augite phenocrysts are rare in both matrix and fiamme. Incipient perlitic structure is seen in both fiamme and matrix, but weathering along the fractures has been minimal.

Densely welded parts of the tuff contain about 6 percent broken and corroded plagioclase phenocrysts, 1 percent augite, and rare hypersthene and biotite suspended in a pale-brown to colorless glassy groundmass (85–90 percent). Accidental lithic fragments of basalt constitute about 4 percent of the rock. Pyroclastic texture is generally not seen because of dense welding in the base of the section and devitrification of the moderately welded section. Composition of the plagioclase phenocrysts ranges from An_{48} to An_{51}. Chemical composition of the tuff from the canyon of the Río Agua Caliente and of the identical-appearing tuff from the Río Conejo in the Caraigres quadrangle suggests that the rocks are dacites (see table 1).

Potassium-argon ages of 147,000±143,000 years for the welded tuff from the canyon of the Río Agua Caliente and 196,000±109,000 years for the welded tuff from the Río Conejo were obtained by R. F. Marvin, H. H. Mehnert, and Violet Merritt (U.S. Geol. Survey, written commun., 1969) and indicate a late Pleistocene age for the rocks.

ASH-FLOW TUFF OF SAN JERONIMO

The ash-flow tuff of San Jerónimo crops out in the Istarú quadrangle only north of the village of San Jerónimo on the road between Urasca and Bajo Congo (the road is not shown on the map). The tuff is welded from top to bottom and is dark gray to black on fresh surfaces and light greenish gray on weathered surfaces. It consists of abundant broken phenocrysts of plagioclase (An_{58}–An_{62}), common euhedral phenocrysts of biotite, rare augite, and hypersthene suspended in an abundant glassy matrix. The unit is about 15 m thick. The chemical composition of the fresh rock suggests a rhyodacite (table 1). Pumice fragments in the upper part of the unit are abundant, unflattened, and weather into negative relief. Pumice fragments near the base of the unit are flattened, greatly elongated, and commonly the site of secondary quartz crystals. The writer has seen similar flattened and elongated pumice fragments that were indicative of fluid movement of the tuff after welding in welded ash-flow tuffs in the southern part of Nevada.

The tuff unconformably overlies the Doán Formation, filling a channel cut into the Doán and dipping 15° NW. The lower contact is locally at the level of the Urasca–Bajos Congo road. Upper surfaces of the tuff appear to be constructional, and overlying rock units are not known.

UJARRAZ FORMATION

Conglomerate, sandstone, and mudstone that crop out along the Río Reventazon between Bajos Urasca and Loaiza were named the "Ujarrás" Formation by Escalante (1966, p. 62). The feature from

TABLE 1.—*Chemical analyses of volcanic rocks from the Cordillera Central and nearby areas, Costa Rica*

[Analyses by Paul Elmore, Samuel Botts, Lowell Artis, John Glenn, Hezekiah Smith, Dennis Taylor, Gillison Chloe, James Kelsey and Blanche Ingram, U.S. Geol. Survey, 1965, 1966, 1967]

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
Volcán Irazú, juvenile bomb:								
1–20–65	56.3	16.8	2.2	4.5	4.7	7.3	3.5	2.3
1–7–65	56.6	17.5	1.8	4.5	4.6	7.3	3.6	2.2
1–6–65	56.6	17.3	1.8	4.5	4.3	7.4	3.7	2.2
Volcán Poás, juvenile bomb: 1953	55.6	17.3	3.2	5.0	4.1	8.1	3.2	.88
Cervantes Formation	55.8	17.7	3.2	3.3	4.4	7.3	3.5	2.2
Birrís Formation	53.0	16.8	2.3	5.7	6.2	8.4	3.0	1.6
Sapper Formation	54.5	17.6	3.2	3.5	3.5	7.3	3.4	2.1
Reventado Formation:								
Upper member	56.2	19.4	3.8	3.5	3.4	3.4	3.5	3.2
Paraíso Member	56.4	18.2	3.0	3.7	3.7	6.6	3.5	2.0
Ash-flow tuffs:								
Río Conejo	60.1	17.2	2.0	2.6	1.3	3.9	3.5	3.5
Río Agua Caliente	61.3	17.2	1.3	3.2	1.5	4.0	3.5	3.1
San Jerónimo	63.3	16.5	1.7	1.6	1.0	2.2	4.3	4.7

	H_2O-	H_2O+	TiO_2	P_2O_5	MnO	CO_2	Sum
Volcán Irazú, juvenile bomb:							
1–20–65	0.38	0.45	1.1	0.41	0.11	<0.05	100
1–7–65	.00	.28	1.1	.41	.13	< .05	100
1–6–65	.00	.38	1.1	.40	.10	< .05	100
Volcán Poás, juvenile bomb: 1953	.22	.52	.96	.43	.15	.19	100
Cervantes Formation	.54	.66	1.1	.04	.12	< .05	100
Birrís Formation	.09	1.0	1.3	.37	.14	< .05	100
Sapper Formation	2.0	.80	1.2	.43	.13	< .15	100
Reventado Formation:							
Upper member	.94	.96	1.0	.25	.11	< .05	100
Paraíso Member	.69	.61	.98	.32	.10	< .05	100
Ash-flow tuffs:							
Río Conejo	1.1	3.2	1.0	.31	.12	< .05	100
Río Agua Caliente	.74	2.6	1.0	.36	.13	< .05	100
San Jerónimo	.37	2.7	.91	.22	.14	< .05	100

which the name was taken is spelled "Ujarráz"; as the misspelled name has appeared in print only once, the correct spelling is used here. The formation is well exposed in the Ujarráz valley, the type locality, but the best exposures are downstream near Joyas in near-vertical cliffs that enclose two small benches. An outcrop of Ujarráz, too small to map, occurs northeast of the Río Birrisito at the foot of a cliff formed by the Paraíso Member.

The Ujarráz in outcrop is a light-yellowish- to light-brownish-gray very poorly consolidated conglomerate and locally is a breccia, interbedded irregularly with poorly sorted friable sandstone and mudstone. Facies changes are abrupt, and individual beds retain their character only for a few meters along strike. Outcrops near the Río Chirí and Río Birrisito, near Loaiza, and in the small benches near Joyas are chiefly very poorly consolidated conglomerate and pebbly sandstone or unconsolidated gravel and sand. Lithic fragments are andesitic, commonly porphyritic, and fresh. They are subrounded and as much as 1 m in diameter. Lithic fragments resemble rocks in the Aguacate and Doán Formations and are unlike those of the overlying Reventado, Sapper, Birrís, and Cervantes Formations. Very friable mudstone and sandstone form the matrix of the conglomerate or gravel and consist of the same types of lithic fragments.

The stratigraphic position of the Ujarráz Formation heretofore has not been clearly established. However, one poorly exposed outcrop and some other evidence suggest that the Ujarráz Formation is overlain by the Paraíso Member of the Reventado Formation. One outcrop of boulder gravel, apparently Ujarráz, is overlain by undoubted Paraíso lava on the east side of the Río Chirí just south of the mapped area. This outcrop supports Escalante's (1966, p. 62) conclusion that the Paraíso is younger than the Ujarráz. Valleys of all streams and creeks that cross the Ujarráz-Paraíso contact have been checked by Escalante and the writer, and all are obscured by recent alluvium. However, artesian springs just downslope from the Ujarráz-Paraíso contact east of the Río Birrisito also imply that the Paraíso may be younger. The springs flow from rise pits in the Ujarráz Formation and discharge as much as 5,000 gallons per minute. The position of the springs in relation to the Ujarráz-Paraíso contact, their artesian flow, and the general absence of springs from the jointed rubble-covered face of the Paraíso escarpment suggest that the artesian water is held in the permeable Ujarráz by a relatively impermeable cap of Paraíso lava and that the water escapes to the surface only where that caprock is absent. The absence of springs on the face of the cliff formed by the Paraíso Member suggests that the springs are not fed by ground water in the Paraíso lava. Drilling of the Ujarráz Formation by the Instituto Costarricense de Electricidad (ICE) indicates that the lower 50 m of the 200-m-thick formation is an artesian aquifer (Edwin Mojica, assistant geologist, ICE, oral commun., 1967). Springs along the contact between the Ujarráz and Cervantes are also common downstream from the Río Urasca–Río Reventazón junction, and springs from the interior of the Ujarráz Formation are common near Joyas. Although many test holes have been drilled into the Ujarráz, none have furnished data resulting in the determination of the relative stratigraphic position of the Paraíso Member and the Ujarráz Formation.

The top of the Ujarráz Formation is at about 1,100 m in altitude in a small bench across the river from Joyas, at about 1,000 m in a small reentrant in the Paraíso Member near Infiernillo, and near 1,100 m in an outcrop near the Río Chirí. Relief on the top of the Ujarráz Formation suggests a slight disconformity. The Ujarráz unconformably overlies the Aguacate Formation and appears to overlie the ash-flow tuff of the Río Agua Caliente disconformably.

PLEISTOCENE TO HOLOCENE SERIES

IRAZU GROUP

The Irazú Group, here named and described, includes from the oldest to the youngest: the Reventado Formation, the Sapper Formation, the Birrís Formation, and the Cervantes Formation, of late Pleistocene to Holocene age and all first described and formally named herein. Rocks composing the Irazú Group crop out over most of Volcán Irazú, the source of the name, as far south as the Río Reventazón and over the major part of Volcán Turrialba which is 1 km northeast of the mapped area. The Reventado and Sapper Formations consist of basaltic andesite lava, ash, and lahar; the Birrís Formation is chiefly basaltic andesite lava; and the Cervantes Formation also consists of basaltic andesite. The Ujarráz Formation is not included in the Irazú Group as its stratigraphic position is subject to question. Widespread but thin recent ash and lahars that cover much of the surface of Volcán Irazú have been disregarded in mapping the area.

REVENTADO FORMATION

Rocks of late Pleistocene age that overlie the ash-flow tuff in the canyon of the Río Agua Caliente and underlie the Sapper Formation are here named the Reventado Formation. The type locality is the canyon of the Río Reventado from the 1,660-m contour to the 2,070-m contour where the major part of the upper member is well exposed. The formation is separated into three units: the lower Paraíso Member; a middle unit of deeply weathered orange- to reddish-brown ash, here informally called the ash-bed member; and an unnamed upper member.

Paraiso Member

The Paraíso Member of the Reventado Formation crops out south and east of the village of Paraíso along the Río Claro; in the Río Regado to the northeast; in an escarpment between San Chirí, in the Tapantí quadrangle to the south, and the Catarata (waterfall) Los Novios; as three inliers near Yas, Flor, and Santiago; and as an escarpment near Birrís and Naranjo. The name "Paraíso" has been informally used in Costa Rica for this section of rocks, and for that reason it is retained. The type section is seen at the Catarata Los Novios southeast of Paraíso. The escarpment face consists of rubble breccia that appears to reflect very closely the original surface of the flow face. Well-developed columnar jointing can be easily seen at the type section near the southern border of the mapped area and in other topographically less spectacular areas where the streams have cut deep reentrants into the member. Columns in the lower part of the member show a pronounced convex flexure toward the south, the direction of flow. Between San Chirí and the Río Regado, the Paraíso Member consists chiefly of two flows. The inliers near Yas, Flor, and Santiago show some surficial breccia rubble, but most are like the rock seen at Catarata Los Novios. Typically, the rocks show fewer flow structures than other lava flows in the Reventado Formation, and phenocrysts are larger. Cliffs in the Paraíso Member along the Quebrada Hondo show thick flows and thin interbedded lahars. The Paraíso Member in the area of the Catarata Los Novios is at least 170 m thick. It is clear that the various flows of the Paraíso Member filled a pre-Reventado low, the valley of the ancestral Río Reventazón.

In thin section, differences between flows of the Paraíso Member and flows of the upper member of the Reventado Formation are chiefly textural and not mineralogical. Coarsely porphyritic augite-andesite makes up the Paraíso Member. Plagioclase phenocrysts in the Paraíso are 4 to 5 mm long, make up 25 to 30 percent of the rock, and range in composition from An_{57} to An_{63}. Commonly the plagioclase phenocrysts show sieve texture produced by abundant irregular inclusions of groundmass material. Augite phenocrysts are 3 to 4 mm across (3–7 percent); hypersthene and bronzite (together 1–3 percent, in one flow 6 percent) and magnetite and olivine (together 1 percent or less) form the rest of the phenocrysts. Augite is euhedral and unaltered, whereas hypersthene and bronzite appear as altered crystals, crystals with augite or amphibole overgrowths, and crystals partly altered to chlorite or serpentine and iron oxide. Olivine is absent in only a very few flows in the Paraíso Member. Commonly it occurs as euhedral crystals rimmed with iddingsite. Smaller olivine phenocrysts are commonly altered to iddingsite and antigorite. The matrix is pilotaxitic or felted, constitutes about 60 percent of the rock, and consists of plagioclase microlites, sparse crystals of clinopyroxene, and rarely olivine and magnetite in a minor amount of devitrified glass. The rock is best called an andesite on the basis of chemical composition alone, but the calcic character of the plagioclase phenocrysts and the presence of augite, olivine, hypersthene, and bronzite compel the writer to follow Williams (1952, p. 163) and call these rocks basaltic andesite.

The Paraíso Member overlies the Ujarráz Formation disconformably and is conformably overlain by the ash-bed member of the Reventado Formation.

Ash-Bed Member

The ash-bed member, here informally named, is a distinctive but thin unit composed completely of ash that forms the nearly flat surface between Caballo Blanco and Paraíso, the hilly country south of Birrisito as far east as the Cervantes Formation, and caps the small benches immediately south of Birrís and at Naranjo. The unit is deeply weathered and consists of fine ash, characteristically a dark orange brown to reddish brown. Bedding is not apparent in any of the many sections studied. Locally, roadcuts and stream valleys expose the lower contact, an irregular surface of clinkery lava rubble, like the surface of the scarp face of the Paraíso Member. The upper contact is everywhere covered by wash from the overlying lahars, but the unit is clearly older than the Cervantes Formation, as outcrops of the ash are present below the Cervantes but never above it. The ash-bed member is perhaps 15 m thick in the thickest sections.

Upper Member

The major part of the upper member crops out best in the canyons of the Reventado, Tiribí, Birrís, Chiquito, Empalanado, Durazno, Canada, and Birrisito Rivers, where continuous outcrops commonly can be traced for 3 or 4 km. Areally persistent outcrops also occur along the middle course of Quebrada Pacayas northeast of Lourdes. Smaller rivers and streams have not cut deeply enough through the surficial ash and lahar to show more than occasional outcrops of the characteristic lava flows. North of the Volcán Irazú–Cerro Pico Piedra divide, outcrops of lava flows are scarce because of the greater ash fall throughout the history of the volcano, secondary alteration, and a greater amount of alluvial and colluvial cover. The upper member is probably more than 600 m thick. However, a complete section is not exposed because outcrops are restricted to gullies and canyons of streams that flow down the dip slope on tops of resistent lava flows. There are at least four areally extensive major lava flows and numerous local flows in the upper member. The broken line drawn on the geologic map from the Asilo Chacon near San Ramón in the west-central part of the mapped area and extended to about 2 km east of Páez in the south-central part marks the front of the oldest lava flow in the upper member. As in the case of the Paraíso Member, the front is steep, breccia covered, and apparently constructional. Where not obscured by soil or surficial breccia, the rock shows columnar jointing. The cliff formed where Quebrada Norberta just north of Cartago crosses the front is typical and about 25 m high. Outcrops of the upper member south of this front consist of lahars. Thoroughly dissected lahar deposits, probably alluvial fans like the Quircot and Cartago fans, cover this lava front in the watersheds of the Birrisito and Parrúas Rivers.

Lava flows as much as 30 m thick interbedded with lahars 2 to 8 m thick constitute most of the upper member. Ash deposits vary greatly in thickness depending on the relationship to the summit vent area; they are generally thinner on the western, southern, and eastern flanks of the volcano and thicker on the northwestern and northern flanks. As in the 1963–65 eruptions, prevailing winds appear to have blown ash to the northwest during much of the history of the volcano. Lower surfaces of individual lava flows are generally uneven, reflecting primary erosional irregularities in the underlying material, generally lahar deposits. These lower surfaces may vary in altitude by as much as 10 m in 40 m distance. Internal flow surfaces, which are also parting surfaces, reflect these changes in altitude and indicate movement of the lava over and around surface irregularities. Tops of the lava flows show only slight erosion; as a result, in sequences of lava flows and lahar deposits, some lahars have even bases and uneven tops, and lava flows have uneven bases and even tops. Not uncommonly, lava flows are seen to overlie previous flows which have been only locally covered by lahar deposits.

Lava flows in the upper member are medium to dark gray and weather to light gray. Flow banding (on weathered surfaces only) and vesicular tops are seen in two of the areally extensive flows; the others show flow structure in the alinement of phenocrysts, but flow banding is absent. In thin section, the basaltic andesite flows of the upper member of the Reventado Formation typically show trachytic texture and a gradation in size of the phenocrysts from coarse to fine. The phenocrysts are plagioclase (30–36 percent), augite (2–7 percent), hypersthene and bronzite (together about 3 percent), and olivine (2–3 percent). The plagioclase phenocrysts range from An_{57} to An_{64}, but the majority are An_{61} to An_{64}. Generally they are 2 mm long, exceptionally 4 mm long, have abundant inclusions of glassy and divitrified groundmass, augite, and magnetite, and commonly are corroded resulting in subhedral outlines. Augite is unaltered and euhedral, whereas bronzite is commonly enclosed in a reaction rim of augite or amphibole (actinolite?). Hypersthene appears as unaltered euhedral crystals and as cores of crystals otherwise altered to chlorite. Olivine generally occurs as small crystals completely altered to iddingsite and antigorite. Exceptionally as in the lowest flow in the upper member of the Reventado Formation, olivine crystals are as much as 2 mm across and show only a thin rim of iddingsite. The groundmass constitutes about 60 percent of the rock. About 85 percent of the groundmass is plagioclase microlites, sparse euhedral clinopyroxene, and magnetite, and the remainder is very sparse devitrified glass. The lavas of the upper member are called basaltic andesites chiefly because of the composition. The term basaltic is used because of the predominantly mafic constituents, including clinopyroxene and orthopyroxene, olivine, and calcic plagioclase phenocrysts.

Lahars in the upper member are soft, easily eroded, and commonly unstable in stream cuts. Rock fragments are abundant and range in size from sand to blocks 5 m on a side, and from angular hard relatively fresh rock to rounded or subrounded clayey ghosts of the former rock that can be distinguished from the matrix only on the basis of color and texture. Commonly the lahar deposits contain lenses of green or greenish-gray clay that show characteristics of bentonite; that is, swelling and extreme plasticity when wet and disintegration on drying. The lahar deposits show no evidence of sorting or internal bedding.

Ash beds uncontaminated by lahar deposits are rare on the eastern and southern flanks of Irazú; the best preserved beds crop out in the canyon of the Río Reventado at Misión beneath lava flows and along the middle course of the Río Tiribí above the María del Rosario electric plant. At Misión the ash beds are hematite-red and no more than 2 m thick. The complete lack of any visible color difference, size range, or bedding suggests that these ash beds were the result of a single ash eruption, possibly initial stages of the eruptions that produced the overlying lava flows, or possibly the result of nuée ardente or glowing-cloud eruptions which produced unsorted ash-flow deposits. Bedded ash as much as 30 m thick crops out in the canyon of the Río Tiribí. There the ash deposits are also very fine grained and mostly converted to clay. The ash is light, very pale orange to pale greenish yellow, and is everywhere well bedded and finely bedded. Laterally the ash beds merge with poorly sorted to nonsorted gravel and pebbly sand and lahar. The ash beds are horizontal and apparently were water laid, possibly in ponds temporarily dammed by landslides or lahar deposits. Neither plant nor animal fossils have been found in the Reventado Formation, and its age is known only in a relative sense as postdating the welded ash-flow tuff in the canyon of the Río Agua Caliente and predating the Sapper Formation. The constructional nature of most of the ridges in areas of outcrop of the Reventado Formation strongly suggests a fairly recent age; the radiogenic age 147,000±143,000 years for the welded ash-flow tuff in the canyon of the Río Agua Caliente confirms a late Pleistocene age for the formation.

The contact with the overlying Sapper Formation is generally obscured by recent ash or by materials not in place. The best exposures are in the canyon of the Río Reventado near the Llano Grande landslide. There a sequence of thick lava flows and lahars of the Reventado Formation shows a steep contact with a section of thick lahars and thin lava flows of the Sapper Formation. The contact on the eastern canyon wall just south of the Quebrada Peñas–Río Reventado junction shows nearly horizontal Sapper lava emplaced in a channel cut into the Reventado Formation. Exposures in the western canyon wall show similar rock sequences and a vertical contact in which the rocks of the Reventado Formation formed a low upstream- and updip-facing cliff before being covered by the Sapper Formation. Material of the Sapper Formation forms the landslide. The form of the contacts and of the former upstream- and updip-facing cliff in the Reventado rocks suggests that a major drainage system had been established before the deposition of the Sapper Formation. Bosses of Reventado lava that rise as much as 10 m above the base of the Llano Grande slide between the Reventado-Sapper contact and the junction of Quebrada Peñas and the Río Reventado may be eroded remnants of the interfluve between a tributary and the ancestral Río Reventado. The basal Paraíso Member appears to lie conformably on the ash-flow tuff that crops out in the canyon of the Río Agua Caliente and disconformably on the Ujarráz Formation.

SAPPER FORMATION

The sequence of 15 or more lava flows, interbedded lahars, and ash beds that disconformably overlie the Reventado Formation in the headwaters area of the Río Reventado is here named the Sapper Formation. The name is taken from the cliffed peak 1.7 km southwest of the active crater of Volcán Irazú where a thick sequence of the formation is exposed. The Sapper Formation is differentiated from the Reventado Formation chiefly on the basis of distinctive lava flows and on the disconformable contact with the Reventado Formation. Lahars within the Sapper and Reventado Formations are much alike. The type locality of the Sapper is in the canyon of the Río Reventado from about 250 m below the Quebrada Pavas–Río Reventado junction to the Volcán Irazú–Cerro Pico Piedra crest. The formation crops out in excellent exposures in the headwaters area of the Río Reventado and its tributaries, Quebrada Pavas and the Río Retes, and in the headwaters area between the Sucio and Blanco Rivers north of Cerro Retes. In the valleys of the Río Reventado and its tributaries, erosion has been sufficient to produce exposures that can be traced continuously for 1 to 2 km. Exposures of the Sapper Formation in the area between Quebrada Casjacal on the north edge of the mapped area and the Río Durazno are poor because of the lack of sufficient downcutting by the streams and because of the rather large amounts of ash in the section and the cover by water-transported ash. Outcrops of the Sapper Formation in the ridge between Esperanza and Finca Las Liebres in the northeast part of the mapped area are areally restricted because of the lack of sufficient erosion. The best exposures in this area are along the course of the easternmost unnamed tributary to the Río Playas.

Sapper lavas characterize the formation and are dense, dark greenish black to black where fresh and dark reddish brown where weathered. Locally, fresh surfaces of the rock are so dark and vitreous that they resemble coal.

Microscopic examination indicates that plagioclase phenocrysts compose 19 to 28 percent of the basaltic andesite flows of the Sapper Formation; remaining phenocrystic minerals are: augite (6–8 percent), hypersthene and bronzite (together 2–5 percent), olivine (about 1 percent, but exceptionally as much as 4 percent), and magnetite and primary biotite (together about 1 percent). The plagioclase phenocrysts are 4 to 5 mm long and characteristically show a clear core with a marginal zone of hematite-red inclusions of glass. This zone of inclusions characteristically gives the vitreous plagioclase phenocrysts a hematite-red color in the hand specimen. Composition of the plagioclase phenocrysts ranges from An_{53} to An_{64}, but most are An_{53} to An_{60}. Hypersthene and bronzite both occur as euhedral crystals, corroded anhedral masses, and as crystal remnants with overgrowths of clinopyroxene and amphibole (actinolite?). Olivine is generally replaced by antigorite and iddingsite, but one flow contains numerous crystals of olivine, unaltered except for thin rims of iddingsite. Biotite, although not easily seen in hand speciman, seems characteristic of the basaltic andesitic flows of the Sapper Formation. It is not found in other rocks known to have been erupted from the Irazú center.

The groundmass, about 63 percent of the rock, shows a pilotaxitic texture and consists of plagioclase microlites, anhedral clinopyroxene, and magnetite suspended in a green partly devitrified glass. Crystalline materials compose from about 55 to 80 percent of the groundmass. Chemical analyses of basaltic andesite flows of the Sapper Formation appear in table 1. Sapper lavas are commonly nonvesicular, and flow banding and microscopic flow structure are generally lacking. Locally, as in the valley of the Río Retes above the Retes landslide, thinner flows contain amygdules of an unidentified zeolite. Rubble zones at the top and bottom of most of the flows are much more common in the Sapper Formation than in the Reventado Formation. These zones consist of autobrecciated lava or alluvium, and all have a soft clayey matrix or a zeolitic cement.

Lava flows constituting most of the southern face of Cerro Cabeza de Vaca and part of Cerro Sapper are atypical in that the rock is a soft or secondarily hardened white to light-brownish-gray remnant of the original rock. The texture is still that of the Sapper lavas seen near the Río Reventado–Quebrada Pavas junction, but the iron-bearing minerals and matrix have been leached, apparently by sulfuric acid-bearing surface waters. The rock superficially resembles a white clay, but examination reveals a silica-impregnated locally chalcedonic rock with ghosts of plagioclase phenocrysts and irregular limonitic blebs, apparently of former olivine and pyroxene. Lava in streams draining the Sapper–Cabeza de Vaca area has been altered largely to a very plastic grayish-green pyrite-impregnated clay, locally also impregnated with silica. This alteration extends as far down the watershed as the major junction of tributaries on the Río Retes. There the rock is impregnated with silica and mottled with pyrite. The alteration affects particular lava flows to the exclusion of others, suggesting a control by ground water, original texture, or chemistry of the rock, but not an association with fumaroles. Outcrops in the headwaters of the Río Durazno and Río Cajón show the same impregnation with silica and pyrite.

Sapper lava between Finca Las Liebres and Esperanza is locally vesicular and lighter colored than lava in the type locality, but these lighter colored lavas retain the characteristic texture and mineralogy of the Sapper lavas described above.

Lahars within the Sapper Formation are much like those of the Reventado Formation, even containing clasts of Reventado lava. Lithic clasts range from sand to blocks as much as 4 m on a side and from angular hard fresh rock to progressively more weathered and rounded clasts. Generally, however, Sapper lahars contain far fewer deeply weathered lithic clasts than the Reventado. Lahars cropping out along the course of the Río Durazno just upstream from San Miguel and lahars about 175 m upstream from the first major tributary junction on the Río Retes are well indurated and are studded with coarse euhedral augite phenocrysts.

The Sapper Formation is disconformably overlain by the Birrís Formation in the headwaters of the Río Birrís west of Cerro Noche Buena. The contact is not well exposed, but the Sapper appears to have been deeply eroded prior to the eruption of the Birrís lavas. Lavas of the Sapper Formation border part of the presently active crater of Irazú and apparently were erupted from that crater. Evidence for eruption of materials of the Sapper Formation from the other three known craters of Irazú is lacking. As fossils have not been found in the Sapper Formation, it can be dated only as post-Reventado and pre-Birrís.

BIRRIS FORMATION

Medium-gray fine-grained lava that disconformably overlies the Sapper Formation and is overlain conformably by the Cervantes Formation is here named the Birrís Formation. The type locality is the canyon of the Río Birrís from Lecheria Birrís to the head of the unnamed branch of the Río Birrís that borders Cerro Noche Buena to the east. The formation is excellently exposed in this area; good but discontinuous exposures are also present along the Gonzalez, Roscavan, Central, and Laguna Tapada Creeks. Outcrops on the northern side of Volcán Irazú are scattered and poor because of geologically recent ash cover. Some poor outcrops are seen along the road to San Gerardo on the north-central border of the mapped area.

The Birrís Formation consists of four or five dark- to medium-gray very finely porphyritic andesitic lava flows that texturally resemble lava flows of the Reventado Formation. Characteristically each flow shows a thin cap of dark-hematite-red clinkery rubble, 15 to 60 cm thick, locally fused, consisting of bombs and lapilli; where this cap has been removed by erosion, the lavas characteristically show a ropy surface.

Both the ropy surface and the trachytic texture suggest an originally very fluid flow. Although the Birrís lava flows superficially resemble the lava flows of the Reventado Formation, the texture and very fine phenocrysts in the Birrís flows distinguish them from the Reventado lava flows in the field. Distribution of the clinkery rubble in the summit vent area strongly suggests that the small unnamed breached cone just east of the Don Diego de la Haya crater was the source of the lavas of the Birrís Formation.

Andesite flows of the Birrís Formation contain 15 to 23 percent plagioclase phenocrysts, 8 to 11 percent augite, and about 1 percent hypersthene and bronzite together. Olivine is lacking. The groundmass (69–78 percent) consists of plagioclase microlites (80 percent or more), some clinopyroxene, and magnetite suspended in a sparse devitrified green material. The plagioclase phenocrysts range from euhedral to anhedral, the latter being extensively resorbed. Composition of these phenocrysts ranges from An_{56} to An_{63}. Commonly they show sieve texture. Augite occurs as euhedral phenocrysts, some with sieve texture, and as overgrowths on hypersthene. Both hypersthene and bronzite commonly are unaltered and euhedral. On the basis of both chemical analyses (table 1) and mineralogy, the lavas are considered to be andesite.

Near Cerro Pasquí, the Birrís Formation is overlain by the Cervantes Formation, but the contact is in most places covered by ash from four adventive ash cones: Cerro Pasquí, two small unnamed cones midway between Cerro Pasquí and the Río Quemadas, and one unnamed cone near San Juan de Chicoa. The areal configuration of the Birrís Formation is clearly the result of a topography developed prior to Birrís time, chiefly on the Sapper Formation and to some extent on the Reventado Formation. High ridges such as that which extends east and southeast of Cerro Sapper and the ridge of Sapper lava south of the head of the Río Pila clearly contained and channeled the Birrís lava flows. In detail, the irregular lower contact of the formation and cliffs in Birrís lava which are 35 to 45 m high but of very short lateral extent both suggest that the Birrís lavas flowed over and smoothed a formerly rough topography in which the creeks and rivers flowed in narrow canyons.

Fossils are lacking in the Birrís Formation, as in all members of the Irazú Group; therefore, the formation can only be said to be post-Sapper and pre-Cervantes in age. The very minor erosion of the Birrís Formation, generally only the removal of the rubble cap in the stream courses, suggests a Holocene age; certainly the formation is much younger than the Sapper and most likely nearer in age to the Cervantes.

CERVANTES FORMATION

Dark-colored blocky superficially scoriaceous basaltic andesite lava flows overlie the Birrís and Reventado Formations that crop out from Pasquí southeast to the Río Reventazón and are here named the Cervantes Formation. The name is taken from the village of Cervantes, the type locality, where exposures of the formation are good. Excellent exposures of the thickest sections are seen in the canyon of the Río Reventazón between Puente

Fajardo and Santiago and in the canyon of the Río Birrís near the Birrís electric plant No. 2, south Birrís. Good surface exposures are seen over most of the area mapped as Cervantes because soil formation has been minimal and is restricted chiefly to the weathering of post-Cervantes ash from the four adventive ash cones between Pasquí and San Juan de Chicoa. South of Las Aguas, the recent ash is appreciably thinner, and the hummocky blocky soil-free surface is well exposed. These ash deposits and recent ash from the summit crater of Volcán Irazú were not mapped because of a lack of sufficient thickness, continuity, and distinctive features. Between Yas and Santiago, the Cervantes Formation shows numerous nearly circular depressions and collapsed lava tubes. There, approximately 30 percent of the surface is bare rock; soil lies in depressions and cavities between the angular blocks that constitute the surfaces of the Cervantes Formation. Collapsed lava tubes are common over the outcrop area and generally do not exceed a kilometer in length and a few tens of meters in width. Exceptionally large collapsed tubes 2 km long and 200 m wide are seen from Finca Leda to the Camino del Cerro south of Boquerón. Another collapsed lava tube 3.4 km long extends from the Camino de Fuentes (road of springs) west of Arrabara along the western border of the Cervantes Formation to the Camino del Pedregal near Yas. This tube is about 200 m wide. Typically, the collapsed tubes show a sinuous channel bound by ridges with smooth gently inclined outer slopes and steep inward-facing scarps. Roughly circular collapse depressions are also present just south of Cipresses and Cervantes.

The lower surface of the Cervantes Formation is extremely irregular; thus, the formation varies greatly in thickness from 0 to approximately 25 m near San Martin and to as much as 220 m where it has filled the canyon of the ancestral Río Reventazón.

Microscopic examination of lava from the Cervantes Formation shows an intergranular pilotaxitic to trachytic texture. The rock contains 23 to 30 percent plagioclase laths 3 to 4 mm long, 6 to 9 percent augite, and 1 to 4 percent hypersthene and bronzite together. As much as 70 percent of the groundmass consists of plagioclase microlites (An_{42}), sparse clinopyroxene, and magnetite in a brown, glassy, or only partly devitrified matrix. Phenocrysts of plagioclase range from clean crystals to those filled with irregular inclusions of groundmass. Augite is present as euhedral crystals and optically continuous overgrowths on hypersthene and bronzite. Hypersthene and bronzite are unaltered; bronzite shows pronounced blue-green-pink pleochroism and in some sections a rim of amphibole (actinolite?). Lavas composing the Cervantes Formation are considered basaltic andesite on the basis of chemical analyses and mineral composition. Juvenile bombs from the 1963–65 eruptions of Irazú are mineralogically and chemically essentially the same as the fresh lava from the Cervantes Formation. (See analyses of both in table 1.)

HOLOCENE ALLUVIAL DEPOSITS

COLLUVIUM

Mixed colluvial and minor alluvial deposits extend from the small unnamed cone east of Don Diego de la Haya crater to beyond the northern border of the mapped area and along the east side of the Río Pila. The upslope contact of the colluvial deposits between Quebrada Gata and Quebrada Ojo de Agua is gradational with ash and lapilli of the cone. The colluvial material consists of a heterogeneous mass of scoriaceous lapilli, fused pyroclastic breccia, and lava fragments that range from 4 mm to 1 m across. Bedding is lacking, and sorting where present is very poor.

ALLUVIAL-FAN DEPOSITS

Easily recognized but deeply trenched alluvial fans have been deposited where the Río Reventado enters the valley of Cartago. The oldest, here named the Quircot fan, is north of the city of Cartago and extends from the village of Quircot on the west to San Rafael on the east, and from about 1,800-m contour on the north to some unknown distance under the Cartago alluvial fan to the south. Erosion and subsequent deposition have removed most of the head of the Quircot fan, but it is clear from the position of remaining outcrops on the west side of the Río Reventado that the head of the fan once extended some distance north on a structural bench that begins southeast of Banderilla. Steep-sided canyon walls that enclosed the bench are still seen bordering the Río Reventado. The Quircot fan consists of weathered debris derived from the Reventado and Sapper Formations. Typically the coarsest debris, porphyritic basaltic andesite boulders and blocks as much as 4 m on a side, is at the head of the fan. Downstream, deposits just above the old turbine site ("Turbina" on pl. 2) contain some large boulders, but most of the material is pebbly sand and clay. Bedding and sorting are very poorly developed. Individual beds, like present mudflows, are chaotic mixtures of fragments that show all sizes and degrees of rounding. Stream cuts in the Quircot fan are nearly vertical, as much as 35 m high, and apparently stable if not undercut. At the abrupt westward bend in the Río Reventado just above the turbine site the river has undercut the western bank for some distance. If erosion on this bank is not prevented by some artificial means, the Reventado will shortly be diverted into a new course along the Río Taras and through the suburb of Taras.

The Cartago fan, here named, is on the southern margin of the Quircot fan and extends south beneath the city of Cartago to the suburb of Guadalupe. The western margin of the fan parallels the Río Taras and has been limited chiefly by erosion and deposition of alluvium by the Taras. The eastern margin of the Cartago fan reaches San Rafael. Boulders of lava from the Reventado Formation as large as 4 m on a side are seen from the head of the Cartago fan as far south as the former Campo Ayala. Bedding in the Cartago fan is only locally and very crudely developed, and sorting is minimal except for a southward lessening of coarse debris.

Compositionally, both the Cartago and Quircot fans are much like the lahars of the Sapper and Reventado Formations except that the quantity of clay is greatly reduced. Comparison of the two fans with the mudflows of 1963–65 strongly suggests that both fans owe their origin to mudflow deposition. The channel of the Río Reventado is now entrenched as much as 10 m in the Cartago fan.

BANDERILLA TERRACE

Sometime after the deposition of the Quircot fan, renewed downcutting, mudflow deposition, and reworking of the previous Quircot deposits resulted in the deposition of the unit here named the Banderilla terrace. The terrace begins just southeast of Banderilla on the east side of the Río Reventado and continues downslope to about the 1,600-m contour. The northern two-thirds of the terrace is on a structural bench on lava flows in the Reventado Formation, and the southern third is in a channel cut in the Quircot fan deposits. The Banderilla terrace is bordered on the east and west by scarps cut in the Reventado Formation and in the Quircot fan. The scarp on the east ranges in height from 40 m in the Reventado Formation to 10 m in the Quircot deposits. It is difficult to separate deposits of the Quircot fan and the Banderilla terrace, as both consist chiefly of mudflow deposits derived from the Sapper and Reventado Formations. The uppermost terrace deposits, however, contain well-bedded, moderately well sorted pebbly sandstone, fine gravel, and sand. The surface of the terrace is soil covered and littered with large boulders much like those on the surfaces of recent lahar terraces and the Quircot fan. Renewed downcutting by the Río Reventado has left the Banderilla terrace as much as 40 m above the present riverbed.

FLUVIOLACUSTRINE DEPOSITS

Areas shown on the map as fluviolacustrine deposits consist of fine sand and silt west of the Río Reventado and south of the Cerros de la Carpintera and of coarse gravel, sand, and silt in the Valle de Ujarráz. Deposits in the Valle de Ujarráz are the least extensive, covering about 10 sq km, but are the most striking. These deposits extend from the eastern end of the valley west to the junction of the Río Agua Caliente and Río Navarro beyond the mapped area to the south and as far south as Orosi and Cachí, south of the mapped area. They overlie the Ujarráz Formation in most of the Valle de Ujarráz, but near the mouth of the Río Naranjo they overlie the Cervantes Formation, which at some recent time dammed the Reventazón valley and formed a lake, probably much like that in which the Ujarráz Formation was deposited.

Fluviolacustrine deposits in the Ujarráz Valley are unconsolidated, generally well bedded and locally well sorted gravel, sand, and silt. Component fragments of pebble to boulder size are generally fresh and subrounded to well rounded; they are of the rock types seen in the Aguacate, Doán, Reventado, Sapper, Birrís, and Cervantes Formations and of diorite from stocks exposed south of the mapped area. Sand and silt consist chiefly of lithic fragments of the same rock types and some plagioclase. Locally these deposits have been reworked by the Río Reventazón, and three terraces have been formed.

A fluviolacustrine plain west of the Río Reventado and south of the Cerros de la Carpintera consists of flat-lying generally bedded fine- to medium-grained quartz sand, silt, and clay. These deposits were derived chiefly from erosion of the Coris and Térraba Formations that encircle the plain on the north, west, and south and from fine-grained flood-borne debris from the Río Reventado. Prior to the installation of drainage tile, the area was a large marsh.

STREAM DEPOSITS

Extensive stream deposits covered irregularly by geologically recent ash (not shown on the map) underlie much of the northwest part of the quadrangle, and alluvium floors most of the major valleys. In the Coliblanco area, in the lower course of the Río Reventado west and south of Cartago, and along parts of the Río Reventazón, these deposits are sufficiently extensive to be delineated on the map. The alluvium is chiefly gravel, sand, silt, and clay.

MUDFLOW DEPOSITS OF 1963–65

Aerial distribution of mudflow deposits in the Cartago area between September 1963 and January 1965 is shown on the geologic map (pl. 2). Debris in these mudflows typically duplicates that seen in the Quircot and Cartago fans. The deposits are only rudely sorted and range from clay to boulders 4 m on a side. When newly deposited, the muds will not hold the weight of a man, but when dry, the same deposits hold up a vertical cliff. All the coarse lithic clasts are hard and relatively unaltered; deeply weathered materials have been ground into sand and clay during the movement of the mudflows downstream.

STRUCTURE

Structure in the mapped area is relatively simple; most of the rocks composing the Ujarráz Formation, the underlying ash-flow tuff of the Río Agua Caliente, and the Irazú Group are undisturbed and show only initial dips or are flat lying. Sedimentary and volcanic rocks of Tertiary age along the southern border of the mapped area are moderately folded and faulted. West- to northwest-striking moderately folded anticlines and synclines offset by northeast-striking right-lateral high-angle faults are characteristic in the Térraba, San Miguel, and Coris Formations in the southwest corner of the quadrangle. Flanks of the folds dip from 35° to 50°, and the folds are mainly symmetrical. A thin sandstone bed at the crest of the anticline northwest of Bermejo has been thrust about 3 m to the northeast. The similarity in direction of this minor thrusting and the direction of displacement on the faults suggest that the faults are right-lateral wrench faults rather than normal faults.

Faults of short length cut the Térraba, San Miguel, and Coris Formations in two small outcrop areas on the southern border of the mapped area. These faults are covered on the north by alluvium and are not traceable in the weathered Aguacate Formation to the south. Direction of movement on these faults has not been determined.

Folds in the Aguacate Formation in the southeast corner of the quadrangle are not sufficiently well exposed or regular enough to permit the recognition of distinct structural elements. That the unit is folded is clear, as the dips (as high as 65°) seen in thin lava flows are much higher than initial dips expected in lava flows of such a thickness. Minor faults that show dip-slip movement of a few tens of meters are known to affect only the Aguacate Formation in this area. Traces of two of the faults near Urasca are gouge filled and no more than 30 cm wide.

Folds are unknown in rocks of the Ujarráz Formation and the Irazú Group. Initial dips range from about 30° to 5°; exceptionally, as on the Río Birrís near San Pablo, initial dips as high as 36° are seen. These high dips resulted from movement of lava flows over a cliff in a previous channel or from movement of the lava flow over a steep flow front. Finely bedded ash in the Misión area and very well bedded lacustrine ash deposits in the canyon of the Río Tiribí above the María del Rosario electric plant are essentially horizontal and were clearly not affected by any postdepositional folding. Known faulting of the Irazú Group is limited to two small faults in the canyon of the Quebrada Pavas, east of the Llano Grande landslide. Both faults appear to be predominantly strike slip, and neither can be traced beyond the creek canyon because outcrops are lacking.

GEOLOGIC HISTORY

Pre-Miocene geologic history is not interpretable from outcrops within the area of the Istarú quadrangle. However, outcrops of the Pacacua Formation 2 km south of the mapped area clearly indicate that a thick sequence of apparently unfossiliferous laterally extensive boulder gravel and pebbly sand was deposited near an elevated volcanic landmass, possibly in the Eocene. Particle size and lack of sorting suggest that erosion must have been rapid and that debris was transported only a short distance. Near the end of this period of coarse clastic deposition, boulder gravel was deposited. This gravel and the lack of unconformities within the Pacacua suggest strong uplift of the volcanic center.

Deposition of the Térraba Formation in the early Miocene (but possibly beginning in the late Oligocene) began with dark-colored carbon-rich mud, probably in epicontinental barred basins. Deposition of this mud and some sand continued until the adjacent landmass was eroded to a low level or completely submerged. Carbonate sedimentation of the San Miguel was interrupted only locally and irregularly by deposition of thin layers of clay. The very fine grained limestone and lenses of bioclastic limestone suggest that renewed transgression and a return to open-sea conditions occurred without interruption.

Sometime after the deposition of the lime mud of the San Miguel Limestone but still in the early Miocene, the area was lifted up. Locally to the southwest, uplift was sufficient to produce an angular unconformity between the San Miguel and subsequent rock units. In the Istarú quadrangle, the San Miguel Limestone and the overlying Coris Formation show only slight disconformity and a thin basal breccia of angular limestone clasts in a matrix of Coris sandstone. Deposition of the San Miguel Limestone was followed by the widespread and apparently nearshore deposition of marine sand of the Coris Formation. These sands were locally cut by channels which were filled with deposits of purer quartz sand and interbedded with accumulations of plant remains, now lignite.

In late Miocene or early Pliocene time, the area was moderately folded and faulted. This minor orogenesis marked the end of marine sedimentation in the area, the beginning of another period of volcanism, and erosion of the previously deposited rocks. Tuffs in the Aguacate Formation south of Tobosi were apparently derived from volcanic centers in the Caraigres area to the southwest where laterally continuous tuffs are much thicker. The coarse volcanic block and boulder conglomerate, lava flows, and breccia of the Aguacate Formation in the southeast corner of the quadrangle were probably derived from local volcanic centers. Moderate folding and faulting also marked the end of the deposition of the Aguacate Formation.

Beginning with the deposition of the Doán Formation, the area was covered with thick, poorly sorted, nearly flat lying coarse volcanic boulder gravel and pebbly sand. These sediments were transported only a short distance from the growing pre-Irazú volcanic pile and from the exposed parts of the Aguacate Formation. To the south the presence of corals and predominantly fine clastic sedimentary beds indicates marine deposition of the Doán Formation.

The Irazú volcanic center became active after the deposition of the welded ash-flow tuff in the southern part of the mapped area. Lavas flowed to the north and covered part of the low-lying Tertiary basin between Nicaragua and Costa Rica; to the south they repeatedly abutted against the highlands composed of the Aguacate, Doán, Coris, San Miguel, and Térraba Formations. At least once early in the history of the Irazú volcanic center, the channel of the ancestral Río Revantazón was dammed, and coarse deltaic and lacustrine boulder gravel, pebbly sand, and silt were deposited. Those sediments now compose the Ujarráz Formation.

During the time of deposition of the Reventado Formation, volcanic activity in the Irazú center and in the Turrialba volcanic center 16 km to the northeast apparently produced almost identical ash and lava. Eruptions of ash and lava alternated irregularly and probably independently in both volcanic centers. Easterly and southeasterly winds, however, caused thicker sections of ash to accumulate on the western and northern slopes; consequently sections on the southern and eastern slopes of both volcanoes contain proportionately more lava than sections on the western and northern slopes. Erosion of the unconsolidated ash and mixture of the ash with angular blocks of lava resulted in a section composed chiefly of lava and lahar. Periods of erosion and nondeposition of volcanic materials occurred throughout the time of deposition of the Reventado Formation, but none appears to have been as long as that following the deposition of the Reventado. Local relief on the Reventado surface was as much as 700 m before the deposition of the Sapper Formation.

Irregular alternation of ash and lava eruptions also typified the time of deposition of the Sapper Formation. Lava flows such as characterize the Sapper are not known from the Turrialba volcanic center, and formational contacts indicate that the Sapper lavas were erupted from the presently active crater of Irazú. A period of erosion and nondeposition of volcanic material again followed the deposition of the Sapper Formation. Local relief on the upper surface of the Sapper is at least 50 m.

Eruption of the Birrís Formation, mostly lava flows similar to those of the Reventado Formation, followed. Distribution of the Birrís depended chiefly on topography developed on the surface of the Sapper Formation and locally on topography of the Reventado Formation. The constructional appearance of the surface of the Birrís Formation and the lack of channeling even through the uppermost thin flows strongly suggest that the Birrís is of very recent age. Flows in the Birrís were erupted from the small, breached but youthful-looking cone which is directly east of Don Diego de la Haya crater (pl. 2).

Flank eruptions from small areas now marked by ash cones between San Gerardo and San Juan de Chicoa produced the Cervantes Formation. These gas-rich and fluid lavas flowed to the south and dammed the drainage channels of the Río Reventazón both in the area of the present Puente Fajardo and in the lower course of the Río Birrís. Both dams were quickly bypassed, but only after the deposition of more deltaic and lacustrine gravel and sand. These deposits overlie the Cervantes and Ujarráz Formations in the Ujarráz Valley. The Cervantes Formation is so young that no organized drainage system has been established, but unquestioned carbon-14 ages for it are not available.

LAND USE AND DEVELOPMENT

Ash erupted from Irazú during the 1963–65 period, covered the upper slopes of the volcano, and killed or defoliated 95 percent of the vegetation in the upper parts of the Río Tiribí, Río Durazno, Río Virrilla, and Río Reventado watersheds. The relative lack of vegetation, the impermeability of the ash cover, and the intense local rainfall led to disastrous mudflows and to problems of slope stability and slope control as well as mudflow control to some degree in all the affected watersheds. These problems were greatest in the Reventado watershed. Because of immediate danger to the city of Cartago, detailed geologic, agronomic, and engineering studies were made of the Reventado watershed in order to prepare a plan for landslide and mudflow control.

VOLCANIC ACTIVITY DURING 1963-65

Activity of Irazú during the 1963–65 eruptive period was similar to that known from the three major preceding eruptive periods of 1723, 1726, and 1917–21, in that only pyroclastic ejecta were produced. Lava flows from Irazú, although seen throughout the section, are historically unknown. Most of the material ejected during this latest period of activity was volcanic ash (4 mm or less in diameter), but small amounts of lapilli (4–32 mm in diameter) and some bombs and blocks (larger than 32 mm in diameter) were also ejected. Most of the ash was "accessory"; that is, derived from materials torn from the conduit of the volcano or from avalanches into the crater. However, some of the ash and most of the lapilli were "essential"; that is, derived from new magma or from only recently cooled lava in the throat of the volcano.

Eruptions of ash and bombs were extremely strong on the first day of explosive activity, March 13, 1963, but activity thereafter settled down to intermittent strong eruptions of ash and ash-poor steam (Murata and others, 1966). Strong eruptions of ash and bombs were recorded during April, May, early July, November, and December of 1963 and in January 1964. The highest magma stand and some of the most voluminous eruptions of both plastic and nonplastic material were during December 1963 and January 1964 (Murata and others, 1966). Production of ash and bombs showed a marked decline after June 1964, but incandescent material continued to be ejected as late as January 1965. Ash eruptions ceased by February 10, 1965; by July 1965 the floor of the crater was occupied by a small lake, and an alluvial fan had smoothed out the formerly rough crater floor. Activity in July 1965 was restricted to the venting of steam from the eastern crater wall and to three boiling mudpots that cut the alluvial fan.

MUDFLOW ACTIVITY 1963-65

Unconsolidated clayey materials exposed at the surface, steep slopes, abundant but intermittent rain, and a lack of vegetation are conditions that characteristically favor the formation of mudflows (Blackwelder, 1928, p. 465–480). Most of these conditions are typically present on the upper slopes of Irazú and have in the past led to mudflows even if volcanic activity did not act as a trigger for accelerated erosion. All these conditions combined to produce costly mudflows on the Río Reventado during and following the recent eruptions. In most of the previous major floods of 1724, 1861, 1928, and 1951, prolonged heavy rains were necessary to produce floods or mudflows in the lower reaches of the Río Reventado. Increased runoff, because of the lack of vegetation and the relative impermeability of the fresh ash cover, changed conditions so greatly that, during 1964, rainstorms of even light intensity (20 mm per hr) and of short duration were sufficient to cause serious floods and mudflows on the Río Reventado.

As many as 46 mudflows formed in the Río Reventado between May 1963 and July 1965 (Instituto Costarricense de Electricidad, 1965, p. 135–139), and five of the 1963 mudflows proved disastrous for the western suburbs of Cartago. The mudflow of December 9, 1963, the most destructive, flooded the western part of Cartago, caused the death of 20 or more people, and destroyed 400 houses and some factories. Supplies of potable water, electricity, and communication via telephone, road, and rail were temporarily interrupted. This mudflow followed a 7-hour rainfall. Mudflows of June and July 1964 were so closely spaced and dumped so much debris into the city that emergency measures to protect the city were severely strained. A protective dike system was within 1 m of being overtopped, and it was necessary to abandon a section of the Inter-American Highway and build another. Mudflows again became common during the 1965 rainy season. The highest mudflows on May 25 (9 m) and May 26 (10 m) destroyed six gabion check dams placed in the main channel of the Río Reventado for mudflow control. These gabion dams consisted of individual steel wire cages, which were made semirigid with a welded steel frame, filled with rock, and wired together.

FACTORS AFFECTING SLOPE STABILITY

The location of landslides and the availability of debris for mudflow formation in the Reventado watershed are controlled by physical characteristics of interbedded lava and lahar in the Reventado and Sapper Formations.

Outcrops of the Reventado Formation along the Río Reventado consist chiefly of interbedded thick lava flows (10–20 m) and relatively thin lahar deposits (2–5 m) and form steep-sided canyons like those from the downstream end of the Llano Grande landslide to the Misión landslide and from the head of the Banderilla terrace to approximately 650 m below the head of the Quircot alluvial fan. In these canyons the Río Reventado flows on the dip-slope surfaces of lava flows and over many nearly vertical waterfalls. The regional dip ranges from 15° to 21° S., but locally, as in the canyon bordering the Misión slide, parting surfaces, which are also flow surfaces, range from horizontal to vertical within 100 m laterally. Spacing of the horizontal joints ranges from 5 to 15 cm; the resulting irregularly interlocked plates are laterally self supporting and thus resist collapse when the underlying material is removed. Lava flows having strongly developed vertical jointing generally show a wider spacing of the joints (30 cm–2 m), but the lack of lateral support allows the lava to collapse if underlying materials are removed, and overhanging valley walls and undercut waterfalls result. Because most of the joints in the rock-floored stretches of the canyons are tightly closed, lava in these areas is resistant to erosion by plucking.

Rubble zones, both at the tops and bottoms of lava flows, are composed of tightly packed angular clasts or cemented subrounded clasts that range in size from sand to boulders. If a cement is present, it is a fine-grained clayey counterpart of the larger clasts. Thicker rubble zones appear to be the tops of lava flows that were superficially chilled and then broken as the underlying molten lava continued to move. Rubble zones having a clayey cement appear to be alluvium. The rubble zones are neither as structurally sound nor as resistant to erosion as the lava flows.

Lahar in the Reventado Formation is unconsolidated and clayey. Clasts range in size from sand to blocks 5 m on a side and in condition from fresh to deeply weathered. The matrix and deeply weathered clasts are clay. Locally the matrix shows characteristics of bentonite—swelling and high plasticity when wet, disintegration on drying. Streamside slopes as high as 70° are known from lahar outcrops in the Reventado Formation. Streambanks cut in such lahar deposits are unstable, and they are the major source for the debris in mudflows.

Outcrops of the Sapper Formation on the Río Reventado and its tributaries consist of lava, lava and lahar interbedded, and lahar. Areas where lava forms the stream floor and banks along the streams react to erosion much like the interbedded lava and lahar of the Sapper and Reventado Formations; that is, streams are enclosed in steep-walled canyons and flow along dip-slope surfaces on the lava flows, and vertical to undercut waterfalls are common where the lava is vertically jointed. As in the interbedded lava-lahar outcrop areas of the Reventado Formation, lava flows are resistant to erosion and protect the easily eroded lahar deposits. The steep-walled canyon from the downstream end of the Prusia landslide to the junction of the Río Reventado and Quebrada Pavas is a typical example of the steep-walled canyons produced by the erosion of interbedded lava and lahar in the Sapper Formation.

Sapper lava in streambeds draining the upper slopes in the Reventado watershed has been largely altered to a plastic clay heavily impregnated with pyrite. Locally the lava has been leached of most of its iron and secondarily impregnated with silica. Both argillized and silicified rocks are structurally unsound, easily eroded, and become involved in landslides.

Lahar in the Sapper Formation shows the same characteristics as that in the Reventado Formation: soft, clayey, easily eroded, and structurally unsound. All active landslides in the Reventado watershed are developed in lahar in the Sapper Formation.

LANDSLIDES

Landslides of various ages have developed along most of the major streams and rivers in the Reventado watersheds, particularly along the Río Reventado. Six major active landslides and three major inactive landslides have been recognized in addition to 20 or more superficial and inactive landslides along the Río Reventado. Both active and inactive slides are in lahar deposits. Two major active slides include thin and discontinuous lava flows, and one major inactive slide includes ash beds and lacustrine volcanic sand and gravel.

ACTIVE LANDSLIDES

LLANO GRANDE LANDSLIDE

Movement of the Llano Grande landslide, named from the nearby village of Llano Grande, was first noted in mid-1964, long after movement in the other major slides was first observed. Movement in this slide began around a small rock quarry just southwest of the Tierra Blanca–Llano Grande bridge. Within a few months the road within the area of the slide as mapped was impassable, the bridge had been destroyed, and the head of the slide had reached about the westward limit indicated on the map. (See pl. 2.) The Llano Grande landslide extends over 48 hectares and has been estimated to contain about 38,000,000 cu m of material. Aerial photographs taken in 1956 indicate that the present slide is simply an older reactivated slide. New movement along the western border of the southern part of the slide has been minimal because fresh scarps are only a few meters high. New movement at the head of the northern part of the slide, however, has been much greater; three new scarps show a progressive drop of 8 to 12 m to the east and an aggregate movement in the vertical plane of at least 35 m. Scarps as much as 3 m high and having an opening of 2 m at the surface have formed over much of the slide surface. The direction of movement at any one point within the slide is along a vector between the direction of regional dip and the direction of the Río Reventado. Direction of movement as measured by planetable survey is shown on the geologic map.

The Llano Grande landslide consists chiefly of lahar and some minor thin and discontinuous lava flows. Clasts range in size from sand to blocks 6 m on a side and are fresh to deeply weathered. Major constituents of the slide are sand and clay. The sand is derived from ash and possibly the attrition of lava, and the clays have formed chiefly from the alteration of ash. Most of the fresh and angular clasts appear to have been derived from the thin lava flows contained within the slide mass. Lenses of plastic swelling clays are common in the face of the slide. When dry, these clays show abundant slickensides, indicative of internal shearing.

Springs are common along the entire slide face during the rainy season, and some flow throughout the dry season. These springs commonly break out of the slide face as a debris avalanche, flow freely for some minutes, and then are buried by the collapse of the undermined material. During a rainstorm the entire face of the slide sheds immense quantities of mud and rock into the stream because of the action of the springs.

PAVAS 1 AND PAVAS 2 LANDSLIDES

Pavas 2, the larger, and Pavas 1, the smaller, are two active landslides that are in about the middle course of Quebrada Pavas (Pavas Creek). Both were first noted in 1964, and both are of small areal extent. Aerial photographs taken in 1956 indicate that Pavas 1, like the Llano Grande landslide, is a reactivated older slide. Margins of the slides are cliffed to about 5 m, and open cracks are common over the entire surface. Pavas 1 and 2 appear to consist entirely of lahar deposits. The contribution of these slides to the formation of mudflows is small.

RETES LANDSLIDE

The Retes landslide consists of a slice of the western part of the Old Retes landslide and the southernmost part of the eastern part of the Old Retes landslide, both reactivated during 1964. The western part of the Retes landslide includes three or four thin lava flows separated by thick lahar deposits. The lavas, well exposed in the face of the Río Reventado canyon south of the Retes landslide, crop out as far as the slip face, from which point they break up and slump downward until all coherence as flows is lost and they are included in the jumbled debris of the slide. As opposed to the other major slides in the Reventado watershed, the Retes landslide appears to be a debris slide rather than a slump; that is, a landslide in which earth and rock move relatively rapidly without backward rotation.

PRUSIA LANDSLIDE

Prusia landslide, named from Finca Prusia and located on the upper course of the Río Reventado, west and slightly south of the Hotel Robert, is a classic example of a slump in which movement toward the river and down the regional slope has taken place in a series of independent units, each of which shows backward rotation. The slide appears to consist of lahar deposits only because lava flows are not seen. As is true of the Llano Grande landslide, springs flowing from the face of the slide create debris avalanches, which undermine and cause the collapse of the overlying material. The face of the Prusia landslide is generally a sodden mass resembling wet gumbo. During rainstorms the rate of mass wastage into the river is greatly accelerated, not by movement of the whole slide, but rather by debris avalanche along the slide face.

SABANILLA LANDSLIDE

The Sabanilla landslide, named from the area of that name, was first noticed as small slumps along the streams in the valley above Sabanilla on the upper Río Reventado. Small individual slumps formed in 1964 have combined, and the area from the head of the small flat just south of Cerro Retes to the stream junction west of the Hotel Robert is now moving. Three tributaries of the Río Reventado have cut deeply into unconsolidated lahar deposits just south of Cerro Retes, and erosion by these streams has resulted in oversteepening and slumping of the streambanks, particularly between the 2,600-m and 2,800-m contours. Open crescentic cracks with low scarps 2 to 3 m high and small terracettes with reverse rotation are present both above and below this steep slope. Although extensive movement has not occurred above the 2,800-m contour, the presence of recently healed crescentic cracks, slopes with reverse rotation, and newly opened crescentic cracks at the head of and along the eastern side of the upper part of the Sabinilla landslide conclusively indicate some recent movement.

INACTIVE LANDSLIDES

MISION LANDSLIDE

The southernmost inactive landslide here called the Misión landslide from the area of that name just west of Tierra Blanca, consists entirely of lahar deposits. The slide is a typical slump, having a very steep head scarp and, as seen just below the road that crosses the slide, reverse rotation. The toe of the formerly active slide is interpreted as a debris fall, which resulted from movement of the mass over a steep canyon wall. The toe of the presently inactive slide is protected by a low rock scarp, about 8 m high, and the slide appears to have been inactive during and since the 1963–65 period of eruptions.

ORTIGA LANDSLIDE

The second major inactive landslide, here named the Ortiga landslide from the area of the same name east of the junction of Quebrada Pavas and the Río Reventado, also consists chiefly of lahar deposits, but some unconsolidated lacustrine sand and gravel crop out along the west-northwest-trending part of the Tierra Blanca–Llano Grande road just east of the former bridge. The toe of the landslide is protected from removal along the northern third of its length by a 5- to 10-m bedrock scarp along the Río Reventado; the southern two-thirds of the toe not so protected was removed early in 1964, and the slide was locally reactivated along the Río Reventado. The head scarp in this slide is neither as steep nor as well developed as that in the Misión landslide, and evidence for reverse rotation of the slide mass is lacking. Hummocky topography and closed depressions, however, easily serve to distinguish the area of the slide from the surrounding more stable smoothly rounded ridges.

OLD RETES LANDSLIDE

The third major inactive landslide in the Río Reventado watershed extends from the junction of the Río Reventado and Río Retes, from which the slide is named, to about the 2,480-m contour on the Río Retes. This landslide consists chiefly of lahar deposits and some structurally weak and thin lava flows. Lahar deposits in this slide are highly plastic and unstable. The head scarp borders the slide on the east, separates the Old Retes landslide from other smaller and otherwise topographically distinct slides on the north, and intersects the channel of the Río Reventado to the south. Movement on this head scarp, as measured from the top of the steep slope to the top of the landslide block, is at least 65 m. The bench formed by this part of the Old Retes slide is well preserved, and its broad eastward-sloping surface indicates reverse rotation of the slide mass. Most of the debris which once constituted the Old Retes landslide west of the Río Retes has been carried downstream by the river.

SUMMARY OF LANDSLIDES

Movement of landslide masses into the streams and channel widening and deepening in the upper part of the Reventado watershed were the two major factors leading to the formation of mudflows on the Río Reventado during the 1963–66 period. Rivers along which active landslides did not develop showed lower mudflow crests, an apparently lesser quantity of debris moved, and mudflows composed chiefly of fresh black ash rather than the weathered lahar deposits that characterize mudflows on the Río Reventado.

Increased runoff because of the relative impermeability of the newly deposited ash cover and the death or defoliation of most of the vegetation in the upper part of the Reventado watershed caused flash floods from mid-1963 to 1966. These floods undercut streambanks of unconsolidated and weathered lahar deposits and removed the toes of old inactive landslides, initiating new slides and reactivating old ones. Four and possibly five of the major active slides in the Reventado watershed are reactivated old slides. Significantly, where toes of the old Misión and Ortiga landslides were protected from removal by bedrock scarps, reactivation of the landslides did not occur.

Stabilization of the active landslides, probably through natural processes rather than man-directed efforts, and an end to flash floods will be necessary before the formation of mudflows will cease. Natural stripping of the new relatively impermeable ash cover and artificial reforestation of the upper part of the Reventado watershed had already slowed the runoff and decreased the number and severity of flash floods, and subsequently mudflows, by mid-1967.

FUTURE PROBLEMS OF LAND USE AND DEVELOPMENT

All land use and development on the upper slopes of Irazú and in certain communities on the flanks of the volcano should be conditioned by the fact that eruptions of ash and lava and the formation of potentially destructive mudflows will recur. Future eruptions of ash will blanket most of the upper slopes of the volcano and kill or defoliate most of the vegetation in that area. Because of strong easterly and southeasterly winds, ash deposits will be thicker and extend to lower altitudes on the western and northwestern flanks of the volcano. Large quantities of ash will be dropped as much as tens of kilometers to the west on the intensively farmed and populated Valle Central Occidental and the chief cities of San José, Heredia, and Alajuela. Such ash falls will kill various pasture grasses and trees and temporarily defoliate citrus trees and coffee bushes, but the human population there will probably not be in imminent danger of death. Less likely are the eruptions that produce rocks like those that floor the Valle Central Occidental. These ash deposits, known as welded ash-flow tuffs, were probably produced by rapidly moving, fluid, very hot ash and gas cloud eruptions like those that destroyed St. Pierre, Martinique, in 1902. The ash-flow tuff of the Valle Central Occidental is a product of the latest, but prehistoric, eruptions of Volcán Barba. (See pl. 1.) Similar ash-flow tuffs were erupted late in the history of Turrialba and Poás Volcanoes (pl. 1) and possibly early in the history of Irazú.

Protective dikes constructed in the western suburbs of Cartago for the containment of mudflows will need to be maintained against probable future eruptions and resulting mudflows. Alternatively, Howard Waldron (U.S. Geol. Survey, oral commun., 1965) has suggested the excavation of a diversion channel for the partial or complete shunting of floodwaters or mudflows on the Río Reventado into a natural settling basin along the Río Taras just north of and including the village of Taras. Either maintenance of the present dike system or use of the Taras area as a settling basin would be costly programs, but the use of the Taras area would be a long-term solution to the problem. If such a solution is accepted, construction within the dike system or within the settling basin should be prohibited and farming should be limited to avoid future disasters. The alarm system currently used to warn of mudflows and eruptions, if abandoned, should be reinstated at the first sign of renewed activity of Volcán Irazú and extended to any other volcano in the area that shows signs of renewed activity.

Although Irazú has erupted only ash during historic time, future eruptions of lava cannot be discounted, for lava flows have been important throughout the life of the volcano. Such eruptions could be either from the summit craters or from the flanks of Irazú.

Deforestation, overgrazing, intensive crop farming on unstable slopes, and the currently unstable condition of streambeds as well as the prospect of future eruptions strongly suggest that land in the upper parts of the Reventado, Durazno, Tiribí, and Birrís watersheds be withdrawn from farming, purchased or leased by the Government of Costa Rica, and returned to a forested condition. Specifically, this should include the land within the watersheds of the Río Reventado and its tributaries, the Río Retes and Quebrada Pavas, as far as the Volcán Irazú–Cerro Cabeza de Vaca divide; the Durazno watershed above 2,500 m to the extension of the ridge east of Cerro Cabeza de Vaca; the Tiribí watershed from above 2,400 m to Cerro Cabeza de Vaca; and the Birrís watershed from Cerro Noche Buena to the summit of the volcano. Restricted areas, chiefly the western slope of Cerro Sapper, Cerro Retes, and the southeastern flank of Cerro Cabeza de Vaca are not presently farmed because they are too steep, too closely gullied where soil covered, or too rocky. These areas will need to be reforested with trees and grasses especially resistant to the effects of heavy ash cover, sulfur dioxide, and sulfuric acid. Crop farming of the areas containing landslides, especially the areas of the Llano Grande and Prusia landslides, should be prohibited, and surface drainage and reforestation programs should be instituted. Reforestation projects in the Tiribí watershed near the María del Rosario electric plant have shown how effective reforestation can be in slowing runoff and stabilizing landslides. Detailed programs for reforestation of the area and control of the landslides have been made for the Government of Costa Rica by the U.S. Agency for International Development.

REFERENCES CITED

American Commission on Stratigraphic Nomenclature, 1961, Code of stratigraphic nomenclature: Am. Assoc. Petroleum Geologists Bull., v. 45, no. 5, p. 645–665.

Blackwelder, Eliot, 1928, Mudflow as a geologic agent in semiarid mountains: Geol. Soc. America Bull., v. 39, no. 2, p. 465–483.

Cooke, C. W., Gardner, J. A., and Woodring, W. W., 1943, Correlation of the Cenozoic formations of the Atlantic and Gulf Coastal Plain and the Caribbean region [chart no. 12]: Geol. Soc. America Bull., v. 54, no. 11, p. 1713–1723.

Crosby, I. B., 1942, Geology of the Virilla Canyon, Meseta Central Occidental, Costa Rica: Am. Sci. Cong., 8th, Washington, D.C., 1940, Proc., v. 4, Geol. Sci., p. 483–494.

Dengo, Gabriel, 1961, Notas sobre la geología de la parte central del litoral pacifico de Costa Rica: Costa Rica Inst. Geog., Nac. Informe Semestral, Julio a Deciembre 1960, p. 43–63.

——— 1962a, Tectonic-igneous sequence in Costa Rica, *in* Petrologic studies—A volume in honor of A. F. Buddington: New York, Geol. Soc. America, p. 133–161.

——— 1962b, Estudio geológico de la región de Guanacaste, Costa Rica: San José, Costa Rica Inst. Geog., 112 p.

Dondoli B., César, and Torres M., J. A., 1954, Estudio geoagronómico de la región oriental de la Meseta Central: San José, Costa Rica, Ministerio Agricultura e Industrias, 180 p.

Eardley, A. J., 1951, Structural geology of North America: New York, Harper & Bros., 624 p.

Escalante, Gregorio, 1965, Geología de la Cuenca Superior del Río Reventazón, en Costa Rica: San José, Costa Rica, Primera reunion de geologos de

instituciones gubernamentales de Centro America y Panama, 22a27 de febrero de 1965, 3 p.
——— 1966, Geología de la Cuenca Superior del Río Reventazón, Costa Rica: Inst. Centroamericano Inv. y Technología Indus., Pub. Geol. ICAITI, no. 1, p. 59–70.
Instituto Costarricense de Electricidad, 1965, Informe sobre el problema del Río Reventado: San José, Costa Rica, Inst. Costarricense Electricidad, 312 p.
Krushensky, R. D., and Escalante, Gregorio, 1967, Activity of Irazú and Poás volcanoes, Costa Rica, November 1964–July 1965: Bull. Volcanol., v. 31, p. 75–84.
Lohmann, Wilhelm, 1934, Stratigraphie und Tektonik des Hochlandes von Costa Rica: Geol. Rundschau, v. 25, no. 1, p. 10–26.
Murata, K. J., Dondoli B., César, and Saenz, Rodrigo, 1966, The 1963–65 eruption of Irazú Volcano, Costa Rica—The period of March 1963 to October 1964: Bull. Volcanol., v. 29, p. 765–796.
Romanes, James, 1912, Geology of a part of Costa Rica: Geol. Soc. London Quart Jour., v. 69, p. 103–139.
Sapper, Karl, 1937, Mittelamerika, Bd. 8, abt. 4, Heft 29 *of* Steinmann and Wilckens, eds., Handbuch der regionalen Geologie: Heidelberg, Germany, Carl Winter, 160 p.
Schuchert, Charles, 1935, Historical geology of the Antillean-Caribbean region: New York, John Wiley and Sons, 811 p.
Umaña, J., 1964, Final geologic report on the Cachí hydroelectric project: Costa Rica, Inst. Costarricense Electricidad, 70 p.
Vaughan, T. W., 1918, Geologic history of Central America and the West Indies during Cenozoic time: Geol. Soc. America Bull., v. 29, p. 615–630.
Weyl, Richard, 1961, Die Geologie Mittelamerikas, v. 1 *of* Beiträge zur regionalen Geologie der Erde: Berlin, Gebrüder Borntraeger, 226 p.
Williams, Howel, 1952, Volcanic history of the Meseta Central Occidental, Costa Rica: Calif. Univ. Pubs. Geol. Sci., v. 29, no. 4, p. 145–180.
Woodring, W. P., 1928, Tectonic features of the Caribbean region: Pan-Pacific Cong., 3d, Tokyo, 1926, Proc., p. 401–431.
——— 1966, Estratigrafía Terciaria de la Zona del Canal y partes adyacentes de la República de Panama: Inst. Centroamericano Inv. y Technología Indus., Pub. Geol. ICAITI, no. 1, p. 43–45.
Woodring, W. P., and Malavassi V., Enrique, 1961, Miocene Foraminifera, mollusks, and a barnacle from the Valle Central, Costa Rica: Jour. Paleontology, v. 35, no. 3, p. 489–497.

U.S. GOVERNMENT PRINTING OFFICE : 1973 O—487-788